THE OPEN UNIVERSITY
A SCIENCE FOUNDATION COURSE

UNIT 32 THE SEARCH FOR FUNDAMENTAL PARTICLES

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THE OPEN UNIVERSITY

STUDY GUIDE

This Unit, which concerns particle physics, has two components: the text and a TV programme 'The search for the W and Z'.

The first point to make about the subject matter of this Unit is that it is in no sense 'wrapped up'—when you are studying the Unit, you will come across a number of questions that have yet to be answered. We shall draw attention to some of these questions and you may well pose some additional ones for yourself. Our account of the search for fundamental particles may not be sufficiently detailed for your taste, so to help to assuage any appetite you may develop for more material on this subject, we have provided suggestions for further reading near the end of the text.

The TV programme mainly concerns material in Section 7 of the text. You can, however, watch the programme with profit at any stage in your studies of the Unit.

Finally, a few words about the unfamiliar particles that you will be meeting in this Unit. You do not need to remember the names of all these particles—you are only required to commit to memory the names of the three *types* of particle that are currently believed to be fundamental, that is, leptons, quarks and gauge bosons.

FUNDAMENTAL PARTICLE

1 INTRODUCTION

> *fundamental* Of the groundwork, going to the root of the matter, serving as a base or foundation, essential, primary, original, from which others are derived ...
>
> *The Concise Oxford Dictionary*, Oxford University Press (1982)

In the world around us, there is a wide variety of inanimate and living matter—plants, animals, rocks, water and so on. But what do these different types of matter ultimately consist of? That question, as you have already seen in this Course, can be answered at several different levels (Figure 1).

All rocks and living organisms are made of chemical compounds, which are really just combinations of atoms, which are in turn simply combinations of electrons, protons and neutrons. Hence, beneath the diversity of the matter around us is an apparent simplicity. But is this the most fundamental possible picture of matter, or do electrons, protons and neutrons themselves have constituents? This is one of the questions that will be addressed in this Unit in our discussion of the search for **fundamental particles**—particles that have *no* constituents (as far as can be told). Such particles are often said to be point-like because they are envisaged to exist only at 'points' in space and to have no shape or size.

The word particle has a special meaning in this Unit—it means 'an entity that is smaller than or has approximately the same size as a proton'. It has been found that there are hundreds of such particles, but that *only very few of them appear to be fundamental.* For example, you will see in this Unit that the electron is currently believed to be fundamental, but the proton and neutron are not, because they have been shown to have constituents.

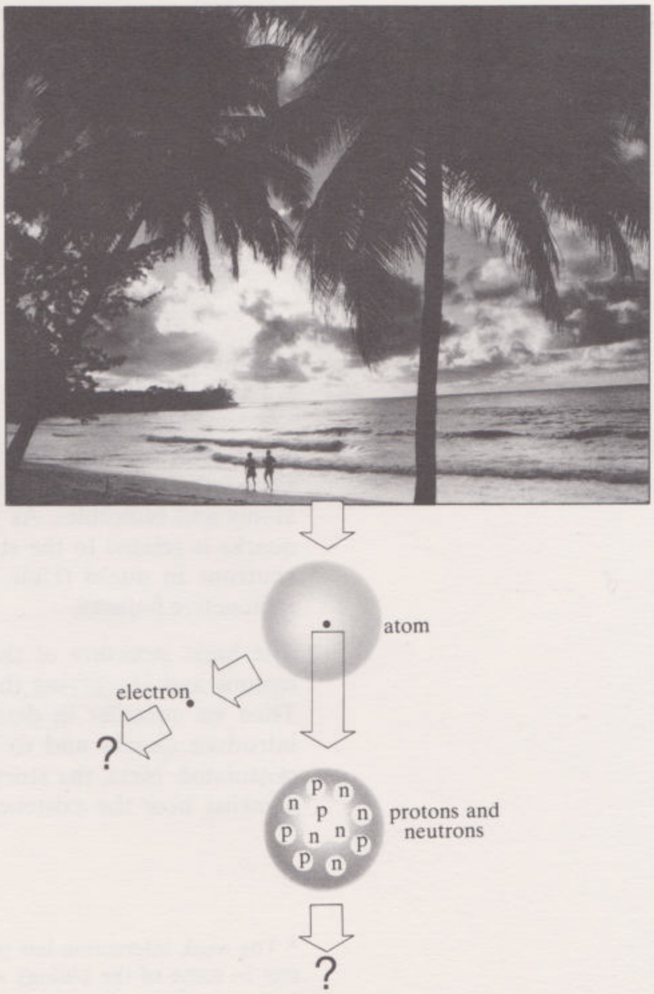

FIGURE 1 Matter consists of atoms which in turn have constituents. Atoms that are heavier than the hydrogen atom consist of electrons and a nucleus containing protons and neutrons. Do electrons, protons and neutrons have constituents?

PARTICLE (HIGH-ENERGY) PHYSICS

FUNDAMENTAL INTERACTION

COSMIC RAYS

The search for fundamental particles involves the interplay of theory and experiment. As you will see in Section 2, the experiments are normally carried out with beams of high-energy particles, which is why the subject matter of this Unit is usually called **particle physics** or **high-energy physics** (the two terms are synonymous). The beams of particles are produced with the aid of machines that accelerate particles to speeds extremely close to the speed of light in a vacuum. In most of these experiments, a beam of particles is directed towards a target, and the subsequent collisions are monitored very carefully in order to study the interactions of particles.

Experiments such as these have led to the identification of three types of fundamental particle: leptons, quarks and gauge bosons (Figure 2). There are now known to exist several varieties of each of these three types of particle. In this Unit, you will see how the existence of several of the fundamental particles was predicted, and you will even be able to predict the existence of some of them for yourself!

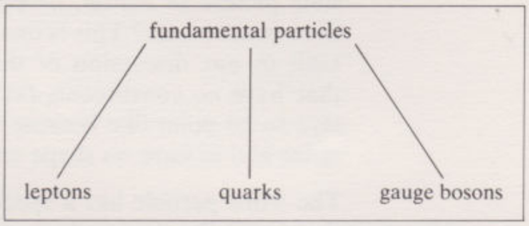

FIGURE 2 There are currently believed to be three types of fundamental particle.

How do the fundamental particles interact? It is currently believed that there are four basically different types of interaction: the gravitational, weak* and electromagnetic interactions, and the strong interaction between quarks (Figure 3). These are known as the **fundamental interactions**, because none of them can yet be understood theoretically in terms of a more basic interaction (just as a fundamental *particle* does not consist of more basic particles).

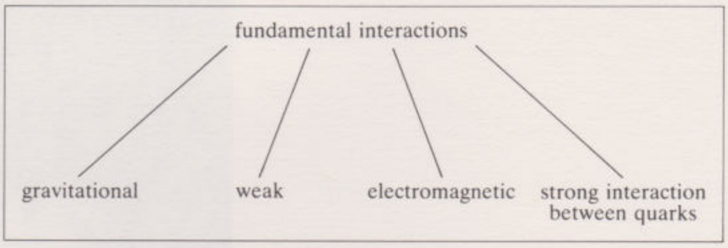

FIGURE 3 There are currently believed to be four types of fundamental interaction.

You have met two of these types of interaction before in this Course. The gravitational interaction (Unit 3), which is experienced by all particles, is responsible for 'holding' you to the ground; the electromagnetic interaction (Units 5–6) is a type of interaction in which any fundamental particle with electrical charge can participate, and is responsible for the structures of atoms and molecules. As you will see later, the strong interaction between quarks is related to the strong interaction that binds together protons and neutrons in nuclei (Unit 31), and the weak interaction is responsible for radioactive β-decay.

The basic structure of this text is very simple. We begin by introducing leptons and identifying the four leptons that were known to exist in 1974. Then we consider in detail particles called hadrons and this leads us to introduce quarks and to identify the first three types of quark that were postulated. Next, the story of leptons and quarks is brought up to date by showing how the existence of more of them has been correctly predicted.

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* The weak interaction has nothing to do with the so-called weak bonds which you met in some of the biology and chemistry Units. These bonds are, in fundamental terms, electromagnetic in nature.

We then go on to discuss the interactions of fundamental particles and, in doing so, introduce the gauge bosons. Finally, we attempt to put the subject of particle physics into perspective relative to the other branches of science that you have met in the Course.

This material may appear to you to be somewhat abstruse and remote from everyday experience. Why have we chosen to end the Course in this way? Well, there are several reasons. First, we want you to see the most fundamental possible picture of matter that can be given according to the present state of scientific knowledge. Second, particle physics is an excellent example of a modern branch of science in which great progress has been made as a result of close cooperation between theorists and experimenters. In a single Unit at Foundation level, we cannot hope to do justice to the mathematical beauty of the theories of high-energy physics, or to the ingenious design of the apparatus used to investigate the behaviour of fundamental particles. However, we have tried to give an idea of the achievements of both theorists and experimenters, and of the extent to which these achievements have been made possible by these two groups of scientists working together.

Finally, we feel that your study of the physical sciences in this Course will be truthful to the continuing scientific quest only if it ends on a note of uncertainty. It should already be clear to you how much more remains to be understood and explained in the *Earth* and *life* sciences. We hope that by the end of this Unit you will appreciate that there are also many important and unanswered questions in the *physical* sciences. These questions are being tackled today in the same spirit of enquiry that informed the study of the planets in the 17th century and the study of atoms in the first half of this century.

Of all the Units of S102, this one contains the most science that could *not* have been taught to a student of S101, because it was not known in 1979, when S101 was first presented. By the same token, a student of S103 will be better placed than you are now to discuss fundamental particles, by virtue of the scientific work going on at this very minute in universities and other institutions throughout the world.

SAQ 1 Which, if any, of the following entities is an example of a fundamental particle? (a) A chlorine molecule; (b) a helium atom; (c) a uranium nucleus.

2 OBSERVING PARTICLES

From the 1930s to the 1950s, most information concerning new particles came from studies of **cosmic rays**, the high-energy particles (mostly protons) that originated in distant parts of the Universe, probably in explosions of stars. A single cosmic ray particle can have a kinetic energy as high as 10^{21} eV, or 160 J, approximately the kinetic energy of a cricket ball delivered by a fast bowler. However, the problem with studying such particles is that it cannot be determined in advance where, when, or with what energy they will arrive.

In order to investigate systematically the behaviour of particles, reliable and intense sources of high-energy particles are required. It has been found that one of the best ways of studying these particles is to make them collide with other matter and then to examine the outcome of such close encounters. In order to study the collisions, scientists and technologists have collaborated to produce high-energy particle accelerators and detectors, and it is with these devices that most investigations of particles are currently carried out.

In this Section, we shall begin by outlining what can happen when two particles collide at high energy, in order to show why studies of collisions are such a fruitful source of information about new particles. Then we shall describe briefly how collisions are produced and studied using accelerators and detectors.

2.1 PARTICLE COLLISIONS AT HIGH ENERGIES

To investigate the structure of matter at the deepest possible level, matter is bombarded with particles of the highest possible energy. To understand why this is necessary remember how scientists have learnt about the structures of minerals, of the DNA molecule and of atomic nuclei (Figure 4). As you saw in the Earth sciences experiment at Summer School, the mineral composition of rocks can be investigated using visible light, whose de Broglie wavelength of approximately 500 nm is small enough to reveal the structures of rocks. In Unit 24, you saw that the molecular structure of DNA was discovered by using X-rays of much shorter de Broglie wavelength, approximately 0.1 nm. The existence and approximate size of atomic nuclei were determined by bombarding matter with α-particles of even shorter de Broglie wavelength, approximately 10^{-6} nm. These examples illustrate the important idea that the shorter the de Broglie wavelength of a probe, the finer is the detail that it can resolve.

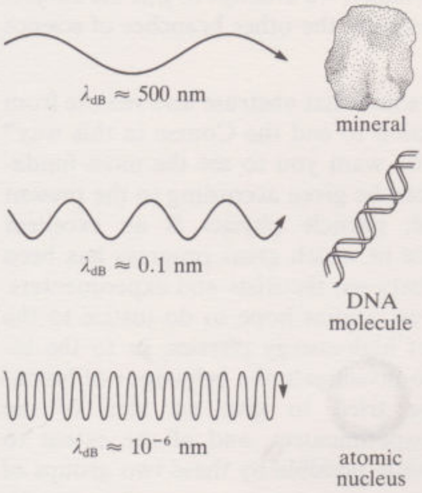
$\lambda_{dB} \approx 500$ nm
mineral
$\lambda_{dB} \approx 0.1$ nm
DNA molecule
$\lambda_{dB} \approx 10^{-6}$ nm
atomic nucleus

FIGURE 4 The shorter the de Broglie wavelength of a probe, the finer the detail that it can resolve. (Note that this diagram is not drawn to scale.)

It should now be clear that to learn about the structure of matter at the deepest possible level, *it is necessary to use particles that have the shortest possible de Broglie wavelength.* The formula for de Broglie wavelength:

$$\lambda_{dB} = \frac{h}{p}. \tag{1}$$

shows that the *shortest* possible de Broglie wavelength corresponds to the *highest* possible magnitude p of momentum. And because momentum increases with kinetic energy, it follows that the shortest possible de Broglie wavelength corresponds to the highest possible energy. Hence, in order to investigate the structure of matter with the highest possible resolution using a beam of particles, it is necessary to use particles that have the highest possible energy.

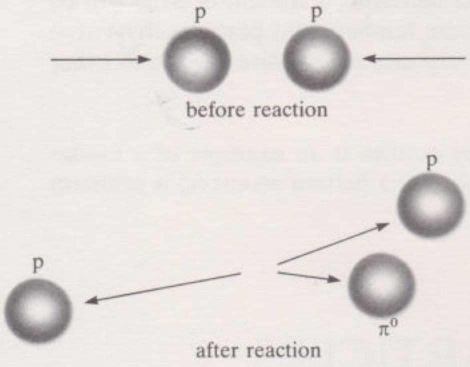

FIGURE 5 If two protons collide at sufficiently high energy, it is possible that a π^0 particle can be created. The energy of the π^0 is derived from some of the energy of the incident protons.

For example, the structure of protons can be investigated by bombarding them with other particles (for example other protons) that have very high energy. In such high-energy collisions between protons, something quite remarkable can happen: *during the collision, new particles* (different from the original protons) *can be formed.* For example, in one commonly observed reaction, a high-energy proton collides with a stationary proton and, during the collision, another particle called a π^0 (pronounced pi zero) is formed, seemingly out of thin air. (You will learn more about the π^0 in Section 4.) This reaction, illustrated in Figure 5, can be written conveniently as an equation:

$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{p} + \pi^0 \tag{2}$$

The π^0 has a rest mass of approximately one-seventh of that of the proton, so the total rest mass of the particles after the collision is actually *greater* than the total rest mass of particles before the collision! This is, in terms of everyday experience, an amazing phenomenon. Think how surprised you would be if you saw, as a result of a collision between two cricket balls, a golf ball emerge out of thin air!

How can a particle be produced in a collision between two other particles? The answer is provided by Einstein's special theory of relativity, according to which an amount of energy has an equivalent mass (Unit 31). More specifically, the theory says that the mass m that is equivalent to energy E is E/c^2, so

$$E = mc^2 \tag{3}$$

where c is the speed of light in a vacuum. It is therefore easy to understand how the π^0 particle is produced in a high-energy collision (Equation 2): the energy equivalent to the rest mass of the particle is derived from some of the kinetic energy of the high-energy proton that collided with the stationary proton. As always, energy is conserved:

$$\begin{matrix}\text{energy equivalent}\\ \text{to total}\\ \text{rest mass}\\ \text{of original}\\ \text{protons}\end{matrix} + \begin{matrix}\text{kinetic}\\ \text{energy of}\\ \text{the original}\\ \text{protons}\end{matrix} = \begin{matrix}\text{energy equivalent}\\ \text{to total rest}\\ \text{mass of the}\\ \text{two protons}\\ \text{and the } \pi^0\end{matrix} + \begin{matrix}\text{kinetic}\\ \text{energy}\\ \text{of the two}\\ \text{protons and}\\ \pi^0 \text{ formed}\end{matrix}$$

Note that the π^0 particle can be formed only if the total kinetic energy of the original protons is sufficiently high. Indeed, the greater the total kinetic energy of the original protons, the more energy is 'available' for the production of new particles.

These arguments apply equally well to all high-energy collisions between particles: *in a sufficiently high-energy collision between two particles, other particles can be created, the energy of the rest mass of each of these newly created particles being derived from some of the kinetic energy of the original particles.*

Just as energy is conserved in every collision, so momentum is always conserved (provided that no unbalanced force acts on the particles). Energy and momentum are examples of conserved *dynamical* quantities; that is, conserved quantities that are associated with the motion of the particles concerned. You will see shortly that there are other types of conserved quantity that *have nothing to do with motion.*

We shall describe shortly how high-energy collisions are studied—how the particle beams are produced, and how the collisions are observed. But now we must pause for a moment to introduce the units of energy and mass that are commonly used in particle physics.

2.2 CONVENIENT UNITS OF ENERGY AND MASS

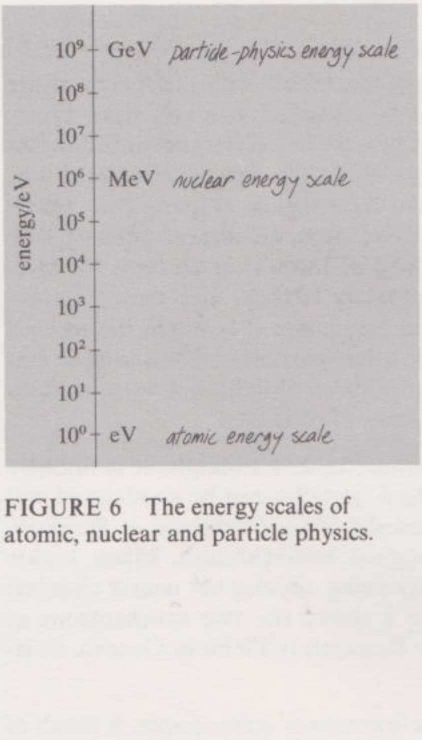

FIGURE 6 The energy scales of atomic, nuclear and particle physics.

In Unit 31, you saw that the energies associated with atomic electrons are typically of the order of between 1 and 1 000 eV, whereas the energies associated with atomic nuclei are typically of the order of *millions* of electronvolts, MeV (Figure 6). If we want to investigate the structure of matter at the deepest possible level, we must use even higher energies, typically greater than or of the order of a thousand million electronvolts, 10^9 eV. This multiple of the electronvolt is called the gigaelectronvolt (GeV) and it is a standard unit of energy in particle physics:

$$1\,\mathrm{GeV} = 10^9\,\mathrm{eV} \tag{4}$$

What about units of mass? It is usual in high-energy physics to measure mass not in units of kilograms but in units of GeV/c^2. In order to see why, consider the rest mass m_p of the proton, $m_\mathrm{p} \approx 1.67 \times 10^{-27}$ kg. Let us find the energy $m_\mathrm{p}c^2$ that, according to Einstein's equation (Equation 3), is equivalent to the rest mass of the proton:

$$\begin{aligned} m_\mathrm{p}c^2 &\approx (1.67 \times 10^{-27}\,\mathrm{kg}) \times (3.00 \times 10^8\,\mathrm{m\,s^{-1}})^2 \\ &\approx 1.50 \times 10^{-10}\,\mathrm{J} \end{aligned}$$

Because $1\,\mathrm{eV} \approx 1.60 \times 10^{-19}\,\mathrm{J}$,

$$m_\mathrm{p}c^2 \approx \frac{1.50 \times 10^{-10}\,\mathrm{J}}{1.60 \times 10^{-19}\,\mathrm{J\,eV^{-1}}}$$

i.e. $m_\mathrm{p}c^2 \approx 9.4 \times 10^8\,\mathrm{eV}$

and, because $1\,\mathrm{GeV} = 10^9\,\mathrm{eV}$ (Equation 4),

$$m_\mathrm{p}c^2 \approx 0.94\,\mathrm{GeV}$$

so $m_\mathrm{p} \approx 0.94\,\mathrm{GeV}/c^2$

This calculation shows that the rest mass of the proton is, roughly speaking, 1 GeV/c^2. Hence, the GeV/c^2 is a very convenient unit in which to measure the rest mass of the proton—it is much easier to remember that the rest mass of the proton is roughly 1 GeV/c^2, than it is to remember that its value is 1.67×10^{-27} kg!

You will see later that there exist many particles with rest masses that are, within an order of magnitude, the same as the rest mass of the proton. That is why particle physicists find the GeV/c^2 such a convenient unit of mass, and why we shall always use this unit in this text. In summary, energy will be measured in units of GeV, mass will be measured in units of GeV/c^2.

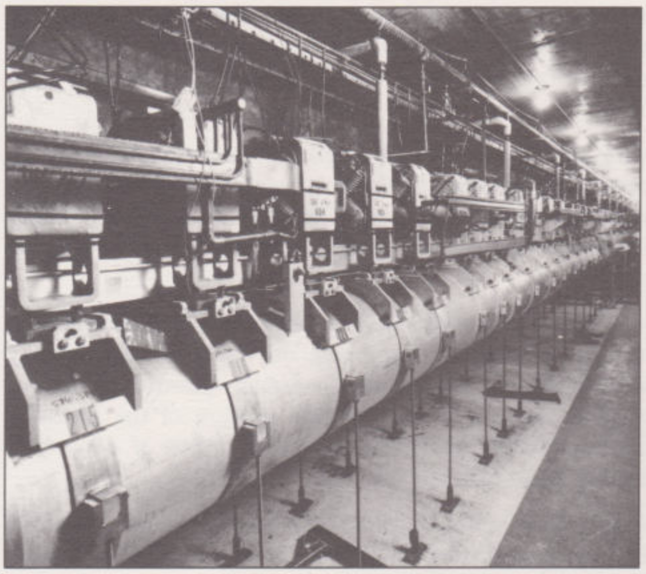

FIGURE 7 Part of the linear accelerator at SLAC in Stanford, California.

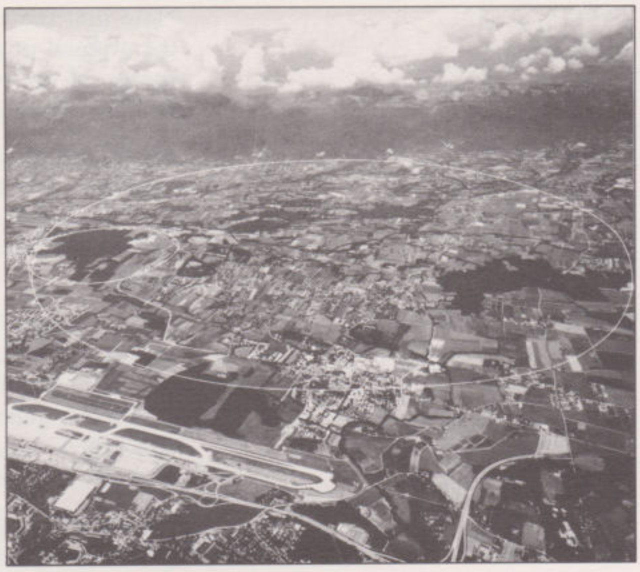

FIGURE 8 There are several synchrotrons at the European Organization for Nuclear Research (CERN) at Geneva, Switzerland. The Large Electron-Positron storage ring (LEP) is indicated by the largest circle. The Super Proton Synchrotron (SPS) is in an underground tunnel, indicated by the second largest circle.

2.3 ACCELERATORS

In particle-physics laboratories, beams of electrically-charged particles are produced using accelerators, which can be classified into two basic types: linear and circular. There is an example of a **linear accelerator** in California at the Stanford Linear Accelerator Centre, SLAC. In this machine, electrons are accelerated by electrical forces down a long tube (Figure 7) in which there is, to most intents and purposes, a vacuum, i.e. almost nothing with which the particles can collide. At the end of their 3 km journey, the electrons have a kinetic energy of approximately 50 GeV, and they are travelling at very nearly the speed of light in a vacuum. It is worth noting that no matter how much electrons (or any other particles with non-zero rest mass) are accelerated, they never reach the speed of light in a vacuum. This is one of the predictions of the special theory of relativity.

Linear accelerators have important limitations. For example, it is unlikely that the maximum kinetic energy to which particles can be accelerated will (in the near future) be much greater than the 50 GeV achieved at Stanford, unless there is an unforeseen technological breakthrough. Much higher energies can be achieved relatively easily using circular (or nearly circular) accelerators called **synchrotrons**. Figure 8 shows the two synchrotrons at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland.

The basic idea behind the design of synchrotrons is quite simple. A batch of particles is made to travel many times in a circular (or nearly circular) path, in a tube in which there is (very nearly) a vacuum. At various points on the path are special devices, called 'cavities', which provide alternating electrical forces to accelerate the protons. Because the particles travel round the path many times, a given cavity can be used to accelerate them many times in succession (Figure 9a). The oscillations of the electrical forces in each cavity have to be *synchronized* with the arrival of the batch of particles so that each time they pass through, they gain energy—hence the name of the machine. This process of synchronized particle acceleration is somewhat analogous to the procedure shown in Figure 9b.

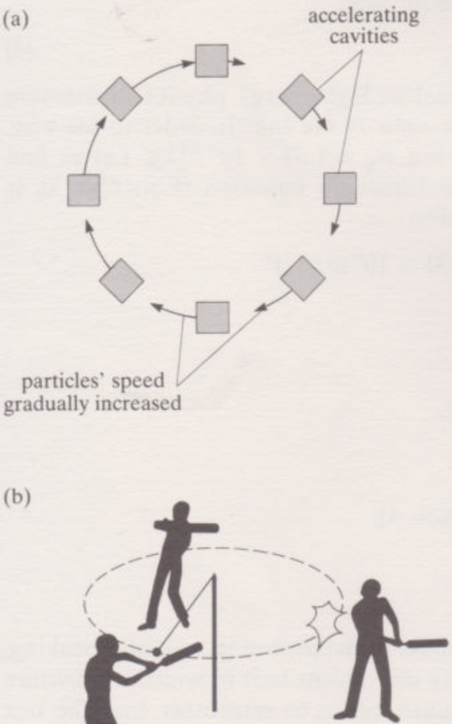

FIGURE 9 (a) In a synchrotron, particles are repeatedly accelerated by the same cavities. (b) An analogy for the basic operation of a synchrotron.

What makes the particles travel in a circular (or nearly circular) orbit? You know from Unit 3 that the force on a particle moving in a circular orbit is always directed towards the centre of the circle. In a synchrotron, the force

LINEAR ACCELERATOR

SYNCHROTRON

FIXED-TARGET EXPERIMENTS

COLLIDING-BEAM EXPERIMENTS

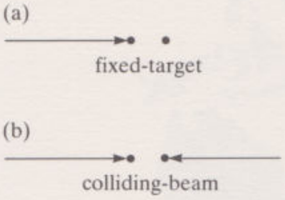

FIGURE 10 Two basic types of collisions studied in particle-physics experiments: (a) fixed-target, (b) colliding-beam.

that keeps the particles travelling in a circular (or nearly circular) path is provided by powerful magnets placed round the path. (You first met the force on charged particles due to a magnetic field in Units 5–6.)

As the kinetic energy of the particles gradually increases, an increasing force is required to keep them moving in the same path, so the strength of the magnetic field must constantly be increased during the process of acceleration. This is achieved by increasing the electric currents flowing in coils that are wound round the iron from which the magnets are made. So you can see that it takes a great deal of technological ingenuity to realize the simple idea expressed in Figure 9.

Remember that the beam of particles is produced so that its collision with a target can be observed. In modern experiments, both fixed and moving targets are used. **Fixed-target experiments** involve, as the name suggests, the directing of a high-energy beam of particles from an accelerator (linear or circular) towards a stationary target (Figure 10a). In contrast, moving-target experiments involve the collision of a beam of particles with another beam that is moving in the opposite (or nearly opposite) direction (Figure 10b). These **colliding-beam experiments** are usually carried out with particles that have been accelerated in synchrotrons.

Colliding-beam experiments have an important advantage over fixed-target experiments: in the former, a higher proportion of the particles' total kinetic energy is available for the production of particles than is the case in the latter type of experiment (assuming that the comparison is made for collisions that involve the same total kinetic energy). In order to understand this, think about the momenta and energies involved in the two types of experiment, before and after the beam and target particles collide.

Consider first a fixed-target experiment (Figure 11a) between a beam particle, with kinetic energy E_k and momentum of magnitude p, and a target (which of course has zero kinetic energy and momentum because it is stationary). Momentum is conserved in the collision: the total momentum of the particles produced in the collision must be the same as the total momentum of the particles before the collision. This implies that the particles (or particle) produced in the collision must *also* have kinetic energy (Figure 11a). Hence, *in a fixed-target experiment, some of the kinetic energy of the beam must always be used in 'giving' kinetic energy to the produced particles (or particle).*

Now consider an analogous colliding-beam experiment that involves the same initial kinetic energy, shared equally between the beam and target particles which have momenta that are of the *same magnitude* but are in *opposite directions*, so that the *total* momentum is zero. The law of conservation of momentum says that the total momentum of the particle (or particles) produced in the collision must also be zero. If a single particle were produced, it would be stationary (Figure 11b)—*all* of the kinetic energy of the original beam and target would have been converted into the energy of the rest mass of the produced particle!

It is actually extremely rare for a *single* particle to be produced in this way. Normally several particles are produced and some of the original particles' kinetic energy is used to give kinetic energy to the produced particles.

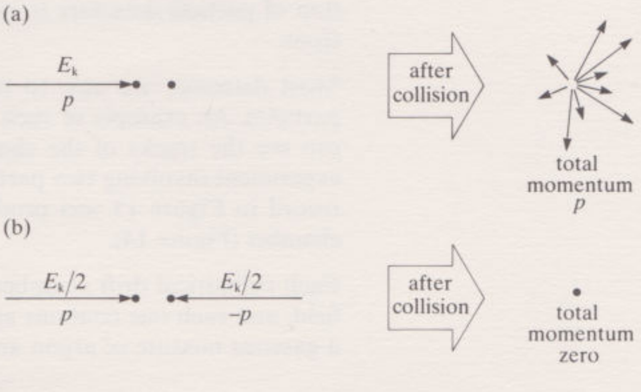

FIGURE 11 In a colliding-beam experiment that involves particles that have total kinetic energy E_k, a higher proportion of this energy is available for the production of particles during the collision than is the case in an analogous fixed-target experiment that involves the same particles with the same total kinetic energy E_k.

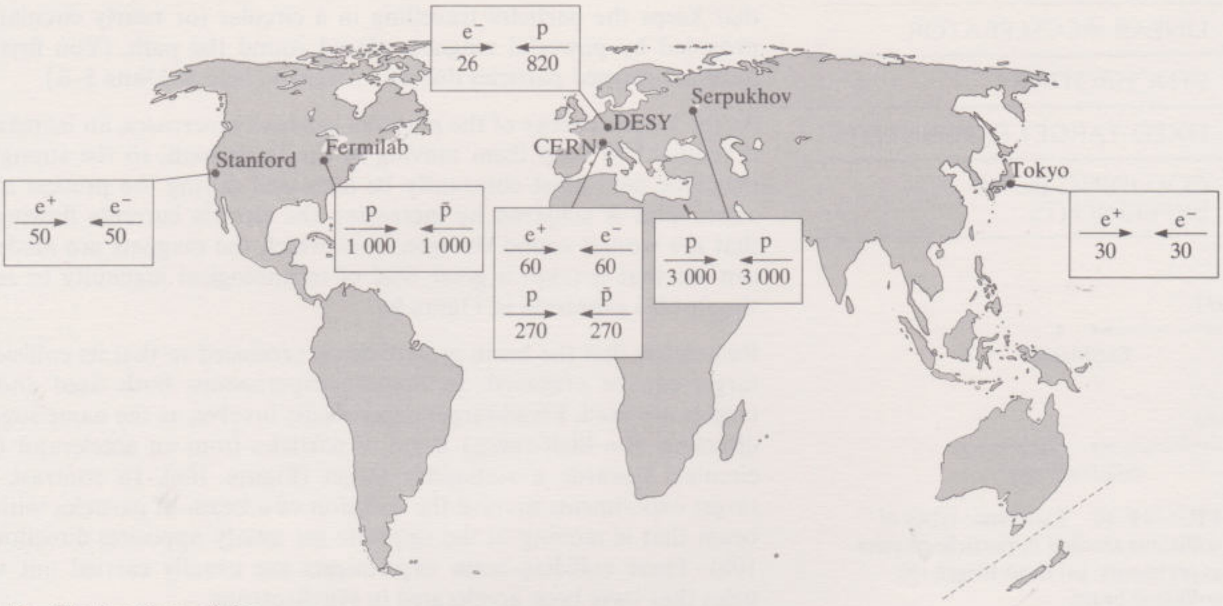

FIGURE 12 The locations of the highest-energy particle accelerators that will used in the 1980s and 90s. For each laboratory, we have shown the highest-energy collisions that it can study. (The numbers below the horizontal arrows refer to the maximum energy, in units of GeV, to which the particle identified above the arrow can be accelerated.) The symbol p̄ denotes an antiproton, which you will meet later, and e^+ denotes a positron (see Unit 31).

However, it is true in general that in a colliding-beam experiment that involves particles with total kinetic energy E_k, a higher proportion of this energy is available for the production of particles during the collision than is the case in an analogous fixed-target experiment involving the same particles with the same total kinetic energy E_k.

This important advantage of colliding-beam experiments has been used to good effect in recent years—as you will see later, no fewer than four fundamental particles have been discovered recently in this type of experiment! However, it would be wrong to give the impression that colliding-beam experiments are invariably superior to experiments involving fixed targets. Indeed, for many purposes, fixed-target experiments are preferable. For example, it turns out that they normally enable many more collisions to be achieved (in a given time) between the beam and the target. Also, the high-energy particles produced in fixed-target experiments are often used to provide the *beams* for other experiments.

Such is the enormous expense of building and operating high-energy particle accelerators that the world has only relatively few particle-physics laboratories. In Figure 12, you can see the locations of the laboratories used in the 1980s and 90s to study collisions at the highest possible energies. The Figure also shows the type of collisions that each laboratory is equipped to study.

2.4 DETECTORS

DRIFT CHAMBER

The interaction between a beam and a target particle normally takes place in approximately 10^{-23} s (ten millionths of a millionth of a millionth of a millionth of a second) and the particles produced travel at speeds close to the speed of light in a vacuum, approximately $3 \times 10^8\,\mathrm{m\,s^{-1}}$! It is the function of particle detectors to provide a record of the outcome of such collisions.

Most detectors are able to record the tracks only of electrically charged particles. An example of such a record is given in Figure 13, in which you can see the tracks of the charged particles produced in a colliding beam experiment involving two particles that each had an energy of 270 GeV. The record in Figure 13 was produced by a type of detector known as a **drift chamber** (Figure 14).

Each cylindrical drift chamber is subject to a constant horizontal magnetic field, and each one contains an array of closely spaced horizontal wires and a gaseous mixture of argon and ethane at low pressure. A high-energy elec-

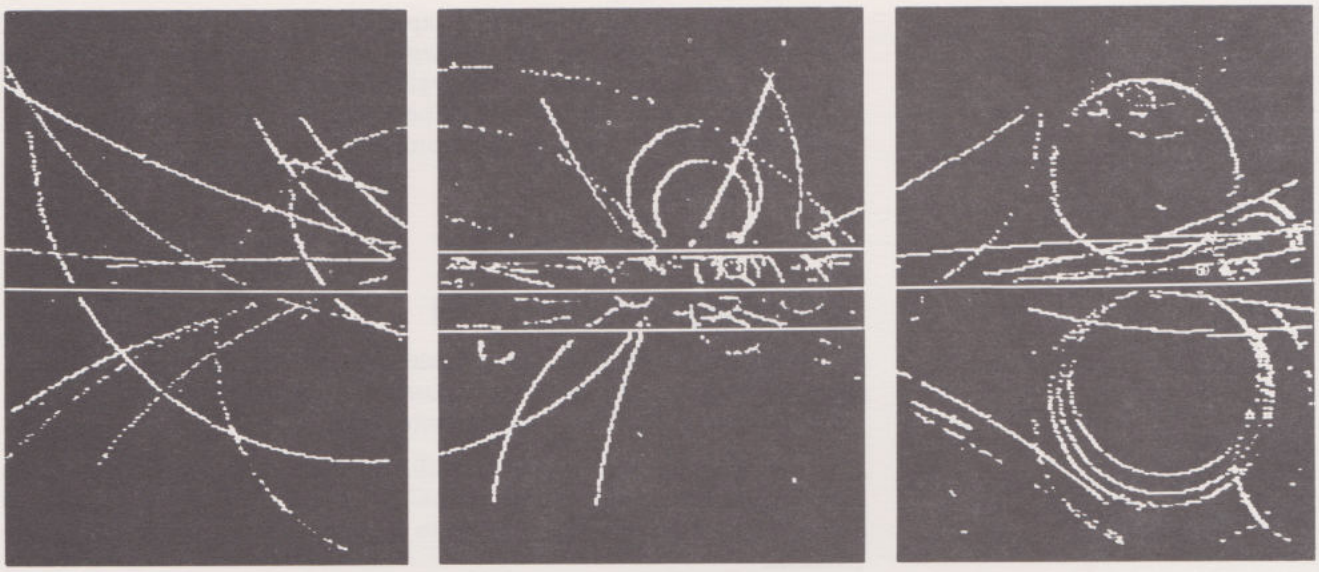

FIGURE 13 Tracks of charged particles that were produced in a head-on collision between two particles that each had an energy of 270 GeV.

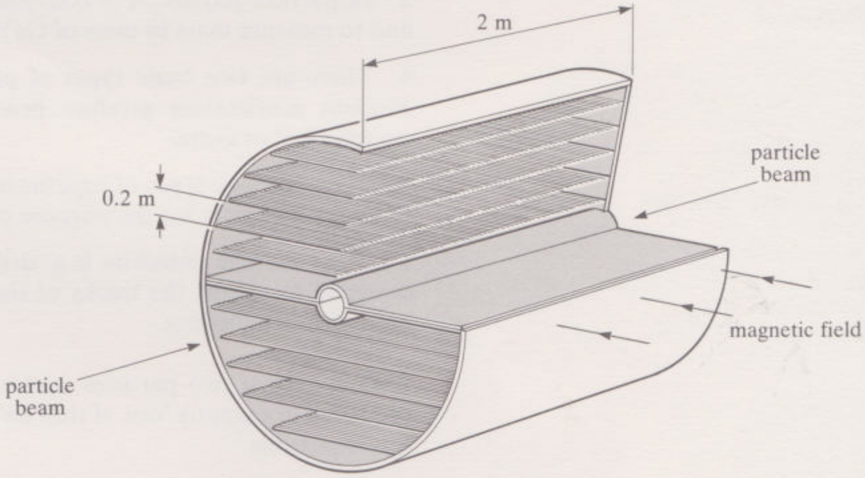

FIGURE 14 A drift chamber. Three of these chambers were used to produce the record shown in Figure 13.

trically charged particle that passes through the chamber ionizes the gas molecules in its path, which then drift to the wires, depositing their charge. The pattern of charges appearing on many wires is recorded electronically and this is later analysed by computer to reconstruct the path of the particle. This apparatus actually enables the determination of the paths of *all* of the charged particles produced in a collision, during the first two millionths of a second after the collision takes place.

After the tracks have been determined, it is necessary to identify the particles that are produced. Also, the energies of the particles are determined, and one way in which this can be done is by measuring the curvatures of their tracks in the magnetic field. The process of data-collecting and analysis is extremely subtle and complicated, and we cannot possibly do justice here to the experimental skills involved. Suffice it to say that, given a visual record such as the one in Figure 13, experimenters can deduce many details about the outcome of the collision. You will see in Section 7 (and in the TV programme) that experimenters at the CERN laboratory in Geneva were able in 1983 to use records similar to the one in Figure 13 to discover two new fundamental particles.

We have discussed only the drift chamber detector, but you should remember that this is not by any means the only type of detector used in particle-physics laboratories. There are several other types of charged-particle detector, and you have already met one in Unit 30—the bubble chamber (Figure 15). Remember, in this device, the tracks of charged particles are observed when they interact with liquid hydrogen that is just below its boiling temperature. There is an example of a bubble chamber photograph on the front cover of these Units.

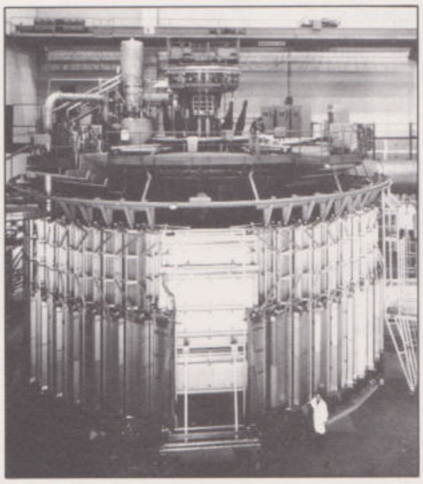

FIGURE 15 This huge bubble chamber (known as BEBC, the Big European Bubble Chamber) was used at CERN between 1973 and 1984. It is now no longer in operation. The chamber was used to take more than six million photographs of particle interactions. (For scale, note the technician at the bottom right of the photograph.)

LEPTON

ELECTRON

NEUTRINO

Finally, it is worth mentioning that experimenters have also found ways of observing, albeit indirectly, the *uncharged* (i.e. electrically neutral) particles that are involved in collisions. Although the tracks of such particles cannot be recorded (because they do not cause ionizations), it is nevertheless possible to determine their energy and momentum.

SUMMARY OF SECTION 2

1 By bombarding matter with particles that have the shortest possible de Broglie wavelength, i.e. the highest possible energy, the structure of matter can be investigated at the deepest possible level.

2 When two particles collide at sufficiently high energy, other particles can be produced: some of the kinetic energy of the original particles is converted into the energy equivalent to the rest masses of the newly formed particles.

3 In particle physics, it is convenient to measure energy in units of GeV and to measure mass in units of GeV/c^2.

4 There are two basic types of particle accelerator: linear and circular. Modern accelerators produce beams of particles that have energies of several GeV or more.

5 There are two types of experiment: fixed-target and colliding beam. The latter type is better for the purpose of producing particles in the collision.

6 Most particle detectors (e.g. drift chambers and bubble chambers) are designed to record the tracks of the electrically charged particles that are produced in collisions.

SAQ 2 When two particles collide at high energy, other particles can be produced apparently 'out of thin air'. Explain, in one or two sentences, why this is possible.

SAQ 3 This question concerns the π^0 particle, which has a rest mass of approximately 2.41×10^{-28} kg.

(a) Can a π^0 leave a track in a drift chamber?
(b) Can the particle be accelerated to a speed of $4 \times 10^8\,\mathrm{m\,s^{-1}}$?
(c) What is the rest mass of this particle in units of GeV/c^2? (Hint: Refer to the back cover, which tells you how many kilograms are equivalent to $1\,\mathrm{GeV}/c^2$.)

SAQ 4 In a colliding-beam experiment at CERN, a particle with a kinetic energy of 270 GeV collides head-on with another particle that has the same kinetic energy.

(a) What is the total kinetic energy of the particles (i) in units of GeV and (ii) in units of joules?
(b) What is the total momentum of the particles?

3 LEPTONS

After we have explained how particles are named in high-energy physics, a family of four **leptons** will be introduced. (The meaning of the term 'lepton' will be made clear later.) Each of these particles is currently believed to be fundamental (i.e. to have no constituents) and each has a corresponding *anti*particle. The properties of these antiparticles will be discussed and then the interactions of the leptons (and their antiparticles) will be considered briefly.

3.1 SYMBOLIZING PARTICLES

In this Section, the simple system that is conventionally used in high-energy physics to symbolize particles will be introduced. The system, which will be used in this Unit, *applies to all types of observed particle, not only to leptons.*

The symbol that is used to denote a given particle normally consists of a letter (or letters) from the Greek or Roman alphabet with a superscript that indicates whether the particle's charge is positive, negative or zero. If there is no superscript, you can normally take it for granted that the particle is electrically neutral. (A common exception is the proton, which, as you know, is denoted simply by p.) Also, it is worthwhile to remember that the charge of every observed particle is always a positive or negative multiple of the charge of the proton, which is conventionally denoted by the italic letter e (e is approximately 1.602×10^{-19} coulombs).

When you come across the name of an unfamiliar particle, this notation is particularly useful because it enables you to deduce the particle's charge immediately. For example, consider the particles τ^-, K^+ and Z, which you will meet later in the Unit:

- The τ^- has charge $-e$ (i.e. approximately -1.602×10^{-19} C).
- The K^+ has charge $+e$ (i.e. approximately $+1.602 \times 10^{-19}$ C).
- The Z has no charge. (The absence of a superscript indicates that the particle is electrically neutral.)

3.2 FOUR LEPTONS AND THEIR ANTIPARTICLES

Perhaps the most familiar member of the lepton family is the **electron** e^-, which was discovered in 1897 by the English physicist J. J. Thomson and which is now known to be a constituent of every atom. Thomson found that the electron has a rest mass of approximately $5.11 \times 10^{-4}\,\mathrm{GeV}/c^2$ and a charge of approximately -1.60×10^{-19} C*. These are the smallest non-zero values of rest mass and charge that have ever been measured, and this lends credence to the idea that the electron has no observable constituents.

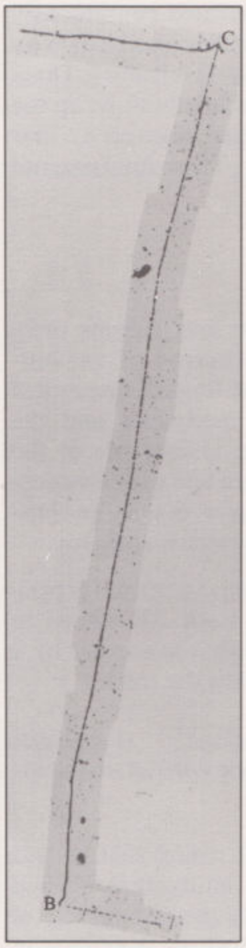

FIGURE 16 The track BC was one of the first μ^- tracks to be observed. The material in which the particle is travelling is a specially sensitized photographic emulsion.

In 1937, another negatively charged lepton was discovered unexpectedly in studies of the collisions between cosmic rays and nuclei in the Earth's upper atmosphere. This new lepton was later called the μ^-, pronounced mu minus. The μ^-, which is now believed to be a fundamental particle, has the same charge as the electron but its rest mass is approximately 207 times that of the electron. One of the first μ^- tracks to be observed is shown in Figure 16.

It was not long before it was found that there existed not only charged leptons but also neutral varieties. In 1931, the physicist Wolfgang Pauli predicted the existence of the **neutrino**, a particle that he suggested would be observed to have zero charge and zero rest mass. By 1956, the existence of Pauli's neutrino ν_e, associated with the electron, had been established and it had been shown that such a neutrino is emitted in each radioactive β^+-decay (Unit 31). Six years later, experimenters also demonstrated that there exists *another* neutrino ν_μ, which is associated with the μ^-.

Each type of neutrino is currently believed to be a fundamental particle, and each one has zero charge and a rest mass that is compatible with zero. However, the results of current experiments do not rule out the possibility of the neutrinos' each having a non-zero rest mass. (All that is known for sure is that the rest mass of the electron neutrino ν_e is no greater than $4.6 \times 10^{-8}\,\mathrm{GeV}/c^2$ and the rest mass of the muon neutrino ν_μ is no greater than $2.5 \times 10^{-4}\,\mathrm{GeV}/c^2$.)

---

* As you saw in Units 11–12, the electron also has spin. This property is shared by many other particles, notably by all other leptons, but we shall not consider it further in this Unit.

Neutrinos can be produced artificially in particle accelerators, but they also occur naturally in abundance. For example, the Sun continuously emits neutrinos (mainly electron neutrinos) at a prodigous rate: approximately 10^{12} (a million million) pass through you every second. They come up through your bed at night, and they rain down on you during the day (Figure 17).

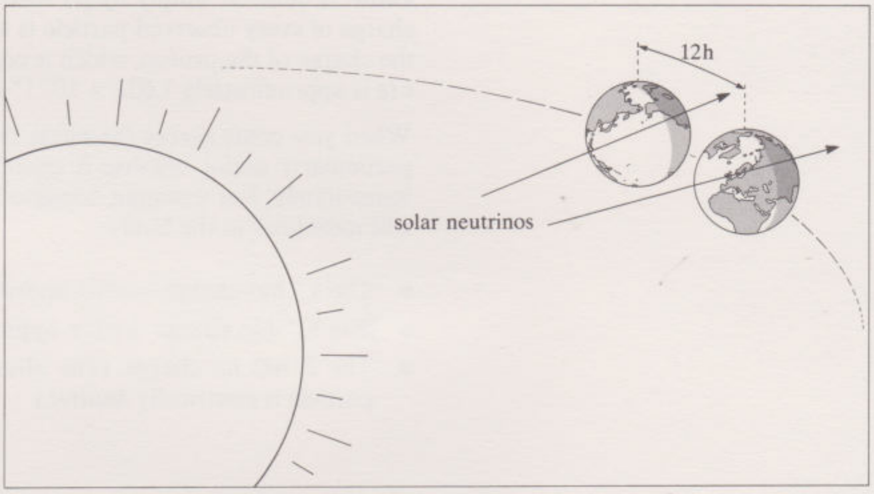

FIGURE 17 Solar neutrinos come up through your bed at night and they rain down on you during the day. (This Figure is not drawn to scale.)

You are probably surprised to learn that you are penetrated continuously in this way, and that this has been going on since you were conceived. Why have you not noticed this before? Why are neutrinos so elusive? These questions will be answered shortly, but let us now pause briefly to recap the leptons that you have met so far: the negatively charged electron e^- and mu minus μ^-, and their associated neutrinos, ν_e and ν_μ. These fundamental particles are normally grouped together like this:

$$\begin{pmatrix} e^- & \mu^- \\ \nu_e & \nu_\mu \end{pmatrix}$$

ANTIPARTICLE

But that is not the end of the story: for each of these four leptons there exists a corresponding **antiparticle** (antilepton). The concept of an antiparticle (antimatter) was introduced in 1928 by the great English theoretical physicist Paul Dirac. He predicted, using quantum mechanics and the special theory of relativity, that there should exist an antiparticle of the electron, with precisely the same rest mass as the electron but with precisely the opposite charge. At the time, no one had ever observed such an antiparticle, and Dirac's prediction was viewed with considerable scepticism.

Four years later in California, Carl Anderson, a young American experimenter working on cosmic-ray physics, observed the track AB shown in Figure 18. On studying the track, Anderson concluded that it was left by a particle that had never before been detected. He wrote that the track

> seemed to be interpretable only on the basis of the existence .... of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron.

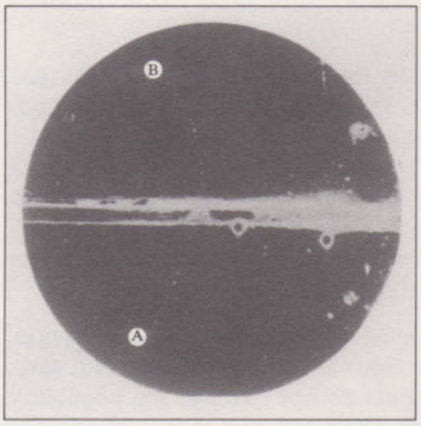

FIGURE 18 The first recorded track of a positron e^+, which in this photograph travels from A to B. The curvature of the track allowed Anderson to deduce that the entity that left the track has positive charge.

Anderson, unaware of Dirac's theoretical work, did not realize that he had been the first person ever to detect antimatter! The entity that he had observed, which he called the positron e^+, was actually the antiparticle of the electron. (You may remember from Unit 31 that a positron is emitted in each radioactive β^+-decay.)

It was later shown theoretically, using quantum mechanics in conjunction with the special theory of relativity, that the concept of an antiparticle applies not just to the electron, it should apply to *all* fundamental particles.

> For every fundamental particle of matter there should exist a corresponding antiparticle that is also fundamental. The particle and antiparticle have the *same* rest mass, but their other properties (e.g. charge) are *opposite*.

Using this result, it is possible to infer the existence of three more antileptons, corresponding to the μ^-, ν_e and ν_μ. The antiparticle of the μ^- is the μ^+ (the mu plus)*, and the two antineutrinos are denoted by $\bar{\nu}_e$ (the electron antineutrino) and $\bar{\nu}_\mu$ (the muon antineutrino). These antiparticles have all been observed, and they are all currently believed to be fundamental. It is conventional to group them together like this:

$$\begin{pmatrix} e^+ & \mu^+ \\ \bar{\nu}_e & \bar{\nu}_\mu \end{pmatrix}$$

You have already met electron antineutrinos in Unit 31, where you saw that one of them is emitted in each β^--decay. This type of radioactive process occurs continually within the Earth (Units 28–29), and consequently about a million of these antineutrinos emerge each second through each square centimetre of horizontal ground on the Earth's surface!

The names, rest masses and charges of the four leptons and four antileptons discussed in this Section are given in Table 1, which has, however, been left incomplete.

TABLE 1 Four leptons and four antileptons

Name	Symbol	Charge /(charge *e* of proton)	Rest mass /(GeV/c^2)
electron	e^-	-1	5.11×10^{-4}
electron neutrino	ν_e	0	≈ 0
mu minus	μ^-	-1	1.06×10^{-1}
muon neutrino	ν_μ	0	≈ 0
positron	e^+		
electron antineutrino	$\bar{\nu}_e$		
mu plus	μ^+		
muon antineutrino	$\bar{\nu}_\mu$		

ITQ 1 Complete Table 1. (You should be able to do this without referring back to the text.)

3.3 THE INTERACTIONS OF LEPTONS AND OF ANTILEPTONS

We shall now review the ways in which leptons and antileptons can interact with each other and with other matter. Consider first the neutrinos and antineutrinos which, remember, each have zero charge and zero (or nearly zero) rest mass. In common with all other particles (and antiparticles), neutrinos and antineutrinos interact gravitationally. This is true even if (contrary to current expectations) they have precisely zero rest mass: the general theory of relativity tells us that all matter and antimatter participate in gravitational interactions, whether or not they have rest mass. You may remember from the TV programmes 'Practically speaking' and 'Voyages of Discovery' the experiment that showed that light, which consists of photons of zero rest mass, is 'bent' by the gravitational attraction of the Sun.

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* The μ^- and μ^+ are often collectively termed muons.

WEAK INTERACTION

☐ Can neutrinos and antineutrinos interact electromagnetically, i.e. do electric and magnetic forces act on them?

■ No, only electrically *charged* fundamental particles are subject to electromagnetic interactions.

It turns out that neutrinos can also interact in a way that you have not met before in this Course—via the **weak interaction**. In order to see just how feeble the weak interaction is, consider again the 10^{12} solar neutrinos that bombard you each second. These neutrinos pass through you almost as if you didn't exist; in fact, it is extremely unlikely that a single one will interact with an atom in your body. (If such an interaction did occur in your body, you certainly wouldn't come to any harm!)

Now consider the interactions of the other four leptons—the electron e^-, the mu minus particle μ^-, and their antiparticles. Because they each have electrical charge, they can interact *electromagnetically*. You may remember from Unit 9 that one of the characteristics of this type of interaction is that stationary particles with charges of the same sign repel each other, whereas stationary particles with the opposite sign attract each other.

TABLE 2 Relative strengths* of three fundamental interactions

Fundamental interaction	Relative strength (order of magnitude estimate)
electromagnetic	1
weak	10^{-3}
gravitational	10^{-36}

* Strictly speaking, these strengths depend on the energies with which the interactions are probed. (The strengths quoted here refer to interactions probed using an energy of 1 GeV.)

The charged leptons (and antileptons) can interact *gravitationally* and it turns out that they can also interact *weakly* with other matter. However, the gravitational and weak interactions are considerably more feeble than the electromagnetic interaction, as you can see in Table 2, which gives the approximate relative strengths of the three basic types of interaction. The data in the Table show that the electromagnetic interaction has approximately a thousand times the strength of the weak interaction, and approximately 10^{36} times the strength of the gravitational interaction.

The feebleness of the gravitational interaction may puzzle you. If its strength is so small compared with those of the electromagnetic and weak interactions, how can it be responsible for holding you down to Earth? The answer is that you and the Earth do not usually interact electromagnetically because both are normally electrically neutral. The dominant interaction between you and the Earth is gravitational, and its magnitude is sufficient to keep you on the planet's surface only because the Earth has an enormous mass (approximately 10^{25} kg). If you were not close to an astronomical object of such a large mass, and were, say, in outer space, you would scarcely be conscious of any gravitational interaction.

If the strength of the weak interaction is 10^{33} times that of the gravitational interaction (Table 2), why aren't the effects of the weak interaction even more obvious than those of the gravitational interaction in everyday life? The answer is that the weak interaction has a *much shorter range* than the gravitational interaction—whereas the range of the weak interaction is only about 10^{-18} m (a tenth of a thousandth of the diameter of a typical nucleus), the range of the gravitational interaction is, like that of the electromagnetic interaction, infinite*.

TABLE 3 Interactions of leptons and antileptons (For ITQ 2)

	Electro-magnetic	Weak	Gravit-ational
e^- e^+		yes	
μ^- μ^+			
ν_e $\bar{\nu}_e$	no	yes	
ν_μ $\bar{\nu}_\mu$			

ITQ 2 Table 3 shows the interactions of the four leptons and four antileptons introduced in this Section. Complete the Table.

The term lepton (which is taken from the Greek word for a small coin) has been used frequently in this Section, but we have not yet specified its meaning. We shall, in fact, postpone doing so until the next Section, where you will encounter particles that are *not* leptons.

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* In order to see that the electromagnetic and gravitational interactions have infinite range, remember that the magnitudes of the gravitational and electrostatic forces between two particles are both inversely proportional to the square of the separation r of the particles concerned: $F \propto 1/r^2$ (Units 3 and 9 respectively), Hence F is non-zero even when r is extremely large.

SUMMARY OF SECTION 3

1 Each fundamental particle has an associated fundamental antiparticle. The particle and antiparticle have the same rest mass, but their other properties (e.g. charge) are opposite.

2 Leptons and their antiparticles, antileptons, are currently believed to be fundamental.

3 Leptons and antileptons interact gravitationally and they each also participate in electromagnetic or weak interactions (or in both).

4 The electromagnetic interaction is stronger than the weak interaction, which is in turn very much stronger than the gravitational interaction (but see the footnote to Table 2).

5 The four leptons and four antileptons discussed in this Section are

$$\underset{\text{leptons}}{\begin{pmatrix} e^- & \mu^- \\ \nu_e & \nu_\mu \end{pmatrix}} \quad \underset{\text{antileptons}}{\begin{pmatrix} e^+ & \mu^+ \\ \bar{\nu}_e & \bar{\nu}_\mu \end{pmatrix}}$$

6 Neutrinos and antineutrinos do not participate in electromagnetic interactions.

SAQ 5 Which one of the following statements about the μ^- and μ^+ is false?

(a) The μ^- and μ^+ have the same rest mass.

(b) The charge of the μ^+ is the same as that of the proton.

(c) The μ^- and μ^+ are each believed to have constituents.

(d) If a μ^- and a μ^+ were to collide, they would interact electromagnetically.

SAQ 6 This question concerns the poem *Cosmic Gall* by the American writer John Updike. First, read the poem carefully.

Neutrinos, they are very small.
  They have no charge and have no mass
And do not interact at all,
The Earth is just a silly ball
  To them, through which they simply pass,
Like dustmaids down a drafty hall
  Or photons through a sheet of glass.
  They snub the most exquisite gas,
Ignore the most substantial wall,
  Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
  And, scorning barriers of class,
Infiltrate you and me! Like tall
and painless guillotines, they fall
  Down through our heads into the grass,
At night, they enter at Nepal
  And pierce the lover and his lass
From underneath the bed—you call
  It wonderful; I call it crass.

(a) Updike refers in the first three lines to the behaviour of 'neutrinos'. Are the properties mentioned in these lines shared by antineutrinos?

(b) In the third line of the poem, Updike says that neutrinos 'do not interact at all'. Why is this not scientifically correct?

(c) Why does Updike liken the passing of neutrinos through the Earth to the passing of 'photons through a sheet of glass'?

STRONG INTERACTION

HADRON

4 HADRONS

We shall now introduce another class of particles called hadrons. You will see that these particles are each characterized by several properties including 'strangeness', a word that will almost certainly have a new meaning for you when you have finished this Section! After the properties of hadrons have been discussed, we shall ask whether they are fundamental particles.

4.1 HUNDREDS OF HADRONS

You saw in Unit 31 that protons and neutrons are bound together in nuclei by the strong interaction, an interaction whose strength is much greater than that of its electromagnetic and gravitational counterparts. Now, experiments (mostly carried out using particle accelerators) have shown that the proton and neutron are only two of hundreds of particles that are subject to the **strong interaction**. These particles are collectively called **hadrons**.

> Hadrons are particles that feel the strong interaction.

Leptons are not subject to the strong interaction, and this property enables a distinction to made between hadrons and leptons.

> Leptons do *not* feel the strong interaction.

π^- 0.1396	π^0 0.1350	π^+ 0.1396			
				n 0.9396	p 0.9383
Λ 1.116					
		Δ^- 1.232	Δ^0 1.232	Δ^+ 1.232	Δ^{++} 1.232
K^0 0.4977	K^+ 0.4937				
			Σ^- 1.197	Σ^0 1.192	Σ^+ 1.189
ϕ 1.020					
Ξ^- 1.315	Ξ^0 1.321		$\bar{K}^0$ 0.4977	K^- 0.4937	

FIGURE 19 Some families of hadrons. (There is no significance to the positions of the families in this Figure.) Notice that the K hadrons are actually grouped into *two* families—they differ in a fundamental property other than charge (as you will see later). The number beneath each hadron is its rest mass in units of GeV/c^2.

The symbols that represent 20 hadrons are given in Figure 19, with their respective rest masses (in units of GeV/c^2). In this Figure, all the hadrons are grouped together in families (each with at least one member) whose members have approximately (or exactly) the same rest mass. Each member is designated by the same Greek or Roman letter, and the superscript as usual denotes its charge, which of course is given in units of the charge e of the proton. (The arrangement of the families of hadrons in Figure 19 is arbitrary.)

The rest mass of each hadron in Figure 19 (and of every hadron observed to date) is non-zero and is within approximately an order of magnitude of 1 GeV/c^2. Hence, hadrons are generally much heavier than the leptons that you met in the previous Section. This explains why the word hadron was chosen to name this class of particles, for the word is derived from the Greek word *hadros*, which means bulky.

It turns out that all hadrons except the proton* are unstable—they sooner or later decay into other particles. The decays of hadrons are classified as strong, electromagnetic and weak. (The gravitational interactions between hadrons, and between individual particles, can be ignored as they are negligible.) These terms refer to the principal interaction involved in a particular decay. The greater the strength of the interaction, the more quickly the decay normally takes place: strong decays normally take place within only 10^{-23} s of the creation of the original hadron, whereas electromagnetic and weak decays take much longer to occur (typically, 10^{-18} s and 10^{-10} s respectively). Later (Section 5) we consider β^--decay, a particularly important example of a weak decay, which you have met several times in the Course.

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* Modern theories predict that the proton is unstable, and the predictions of the theories are consistent with the experimentally determined lower limit of the proton's half-life, which is about 10^{32} years! Neutrons can be stable when they are in nuclei, but when free they decay within about 15 minutes ($n \rightarrow p + e^- + \bar{\nu}_e$).

We shall not be much concerned in this Unit with the differences between the three types of decay, and you will not be asked to differentiate between them.

Before we go on to consider further the properties of hadrons, it is worthwhile to pause for a moment to consider the meaning of *charge*, an electrical property with which you are already familiar. When it is said that a hadron (or any other particle) has charge, a statement is implicitly being made about the effect the particle can have on other particles. For example, a π^- particle will be attracted to any positively charged particle, and it will be repelled by any negatively charged particle. On the other hand, a π^+ particle (which has the same mass as that of the π^-, but opposite charge) has a different effect on other charged particles—it is *repelled* by positively charged particles and *attracted* to negatively charged particles. The charge of a particle is simply a property (a label, if you like) that gives information about the electromagnetic effects that the particle can have on other particles, just as the mass of a particle tells us about the gravitational effects that the particle can have on other particles.

The unit used to express the numerical values of the charges of particles is not important. We are free to *choose* the charge of any charged particle as our unit of charge, then we can measure the charges of all other particles in terms of the chosen unit. As you have already seen, it is conventional to choose the charge of the proton to be +1.

You will see next that studies of the behaviour of hadrons have shown that each hadron is characterized not only by its charge, but also by other analogous properties.

4.2 PROPERTIES OF HADRONS

You saw in Section 2 that energy and momentum are conserved dynamical quantities: for each one, its total value before an interaction is equal to its total value afterwards. Now it is found experimentally that some collision and decay processes that *in principle* are allowed according to energy and momentum conservation, have *in practice* never been observed to occur—they appear to be 'forbidden'. In order to explain this phenomenon, it is essential to ascribe a small number of *intrinsic* properties to each hadron and to assume that each of these properties is conserved in each interaction. It is important to note that a conserved intrinsic property does not depend in any way on the motion of the hadrons.

Three intrinsic properties will now be discussed, beginning with a property that is already very familiar to you, that is, charge.

4.2.1 CHARGE AND ITS CONSERVATION

You have already seen that the electrical charge Q of each hadron is conventionally measured in units of the charge e of the proton. It has been found experimentally that, in *every* interaction that has ever been observed (between hadrons and indeed between *all* particles and antiparticles), charge is conserved—the total charge of all the particles *before* the interaction is equal to the total charge of the particles *after* the interaction. In other words, no reaction has ever been observed in which the total charge before and after the reaction are different.

BARYON NUMBER

An example should make clear this idea of charge conservation. The strong interaction below, in which a π^- and a proton collide at high energy with the formation of a K^+ and a Σ^- particle, has frequently been observed (Figure 20):

$$\begin{array}{lccccl} & \pi^- + p & \rightarrow & K^+ + \Sigma^- & & \text{observed} \\ \text{charge } Q & \underbrace{-1 \quad 1} & & \underbrace{1 \quad -1} & & \\ & 0 & = & 0 & & Q \text{ conserved} \end{array}$$

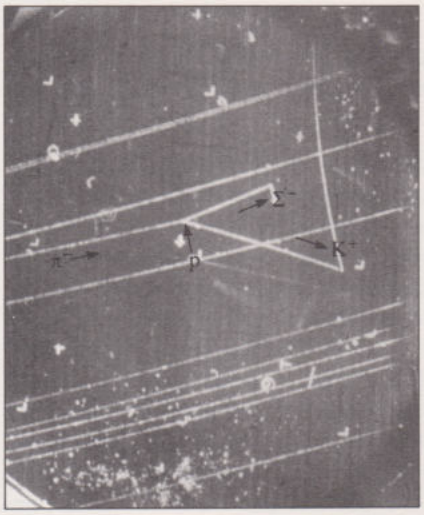


FIGURE 20 A record, obtained using a bubble chamber, of the collision between a π^- and a proton (the nucleus of a hydrogen atom in the chamber) in which a K^+ and a Σ^- are formed.

However, the following reaction between a π^- and a proton has *never* been observed, even when there is in principle sufficient energy available for the K^+, Σ^- and π^- to be produced:

$$\begin{array}{lccccl} & \pi^- + p & \nrightarrow & K^+ + \Sigma^- + \pi^- & & \text{not observed} \\ \text{charge } Q & \underbrace{-1 \quad 1} & & \underbrace{1 \quad -1 \quad -1} & & \\ & 0 & \neq & -1 & & Q \text{ not conserved} \end{array}$$

The fact that this reaction has not been observed is easy to understand in terms of charge conservation: it does not occur because charge is not conserved in the reaction.

The law of charge conservation is extremely useful because it allows us to predict reactions that will *not* occur. For example, the law predicts that these two decays will never be observed because they contradict the law:

$\Xi^- \nrightarrow \Lambda + \pi^+$ Q not conserved

$\Sigma^+ \nrightarrow \Lambda + \pi^-$ Q not conserved

These predictions have been borne out experimentally, because these decays have never been observed.

ITQ 3 Which one of the following reactions is forbidden because it would involve the non-conservation of charge?

(a) $p + p \rightarrow p + p$

(b) $p + p \rightarrow p + p + \pi^+ + \pi^-$

(c) $p + p \rightarrow p + p + \pi^+ + \pi^- + \pi^+$

4.2.2 BARYON NUMBER AND ITS CONSERVATION

When two protons collide at high energy and interact strongly, the reactions

$$p + p \rightarrow p + p + \pi^0 \qquad (2)^*$$

$$p + p \rightarrow p + p + \pi^+ + \pi^-$$

have frequently been observed to occur. Not surprising, you may think—charge is conserved in both cases. However, there are many interactions that have never been observed *even though they are allowed by charge conservation.* For example:

$$p + p \nrightarrow p + p + n \qquad (5a)$$

$$p + p \nrightarrow p + p + n + n \qquad (5b)$$

$$n + p \nrightarrow n + n + p \qquad (5c)$$

$$n + p \nrightarrow n + p + p + \pi^- \qquad (5d)$$

Why don't these reactions occur? The question can be answered by using the concept of **baryon number**, a property that is somewhat analogous to charge. It is found that in order to explain why certain interactions appear to be forbidden it is necessary to assume that:

(i) Each hadron has an associated value of baryon number B (some examples are given in Table 4);

TABLE 4 Baryon numbers of some hadrons

Hadron	Baryon number B
p	1
n	1
π^-	0
π^0	0
π^+	0

(ii) Each lepton and gauge boson (to be discussed later) has baryon number zero;

(iii) The total baryon number of all the hadrons *before* a strong interaction is equal to the total baryon number of the hadrons *after* the interaction—baryon number is conserved.

The baryon number of the proton is defined to be +1, and from this definition a unique value for the baryon number of every other particle can be deduced by assuming that baryon number is conserved in every strong interaction. For example, if a single new particle C is produced in a collision between two protons, it follows from baryon number conservation that the baryon number of C is zero:

$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{p} + \mathrm{C} \qquad \text{observed}$$
$$B \quad \underbrace{1 \quad 1} \quad \underbrace{1 \quad 1 \quad 0}$$
$$2 \; = \; 2 \qquad B \text{ conserved}$$

Particle C should then have this same value of baryon number $B = 0$ *in all other interactions.*

What makes the idea of baryon number so useful is the experimentally observed fact that one can ascribe a *unique* value of baryon number to every hadron—once the value of a hadron's baryon number has been determined in one interaction, the same value can be used in all other interactions. This allows us to predict whether an interaction will or will not occur. Remember, only reactions in which baryon number is conserved are observed in practice.

Baryon number conservation easily explains why the four strong interactions 5a–5d do *not* occur. In each of them, baryon number is *not* conserved:

$$\mathrm{p} + \mathrm{p} \not\rightarrow \mathrm{p} + \mathrm{p} + \mathrm{n} \qquad \text{not observed} \qquad (5a)^*$$
$$B \quad \underbrace{1 \quad 1} \quad \underbrace{1 \quad 1 \quad 1}$$
$$2 \; \neq \; 3 \qquad B \text{ not conserved}$$

$$\mathrm{p} + \mathrm{p} \not\rightarrow \mathrm{p} + \mathrm{p} + \mathrm{n} + \mathrm{n} \qquad \text{not observed} \qquad (5b)^*$$
$$B \quad \underbrace{1 \quad 1} \quad \underbrace{1 \quad 1 \quad 1 \quad 1}$$
$$2 \; \neq \; 4 \qquad B \text{ not conserved}$$

$$\mathrm{n} + \mathrm{p} \not\rightarrow \mathrm{n} + \mathrm{n} + \mathrm{p} \qquad \text{not observed} \qquad (5c)^*$$
$$B \quad \underbrace{1 \quad 1} \quad \underbrace{1 \quad 1 \quad 1}$$
$$2 \; \neq \; 3 \qquad B \text{ not conserved}$$

$$\mathrm{n} + \mathrm{p} \not\rightarrow \mathrm{n} + \mathrm{p} + \mathrm{p} + \pi^- \qquad \text{not observed} \qquad (5d)^*$$
$$B \quad \underbrace{1 \quad 1} \quad \underbrace{1 \quad 1 \quad 1 \quad 0}$$
$$2 \; \neq \; 3 \qquad B \text{ not conserved}$$

It is worth stressing that in every reaction baryon number and charge are *both* conserved. If you write down a reaction in which *either* of the two properties is not conserved, you can be sure that the reaction has not been observed.

ITQ 4 Which one of the following reactions is forbidden because either charge or baryon number (or both) is not conserved? (Refer to Table 4.)

(a) $\mathrm{p} + \mathrm{p} \rightarrow \pi^+ + \mathrm{p} + \mathrm{n}$

(b) $\mathrm{p} + \mathrm{p} \rightarrow \pi^+ + \mathrm{p} + \mathrm{n} + \mathrm{n}$

(c) $\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{p} + \pi^0 + \pi^0$

MESON

BARYON

STRANGENESS

It is useful to classify hadrons into three types (Figure 21): those with zero baryon number, the **mesons**; those with baryon number one, the **baryons**; and those with baryon number minus one, the antibaryons. Hence the proton and neutron (p and n) are baryons and the π^-, π^0 and π^+ are mesons.

It was once believed that baryons are generally heavier than mesons (the word baryon is derived from the Greek word *barus* meaning heavy). However, recent experiments have shown that some mesons are heavier than some baryons, as you will see in Section 6.

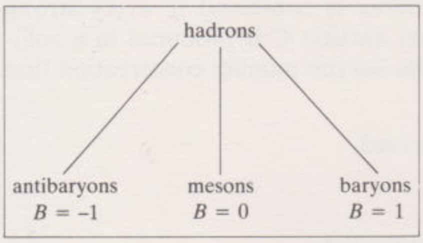


FIGURE 21 Each hadron observed to date can be classified as either an antibaryon ($B = -1$), a meson ($B = 0$) or a baryon ($B = 1$).

4.2.3 STRANGENESS AND ITS CONSERVATION

In the mid-1950s another property of hadrons was postulated by the American theoretical physicist Murray Gell-Mann and (independently) by the Japanese theoretical physicist Kazuhiko Nishijima. This property was called **strangeness** by Gell-Mann, who subsequently introduced several other whimsical terms into the vocabulary of particle physics, as you will see later.

The strangeness S of a hadron may be introduced in exactly the same way as charge Q and baryon number B were introduced:

(i) Each hadron has an associated value of strangeness S.

(ii) Each lepton and gauge boson has zero strangeness.

(iii) The total strangeness of all the hadrons before a strong interaction is equal to the total strangeness of the hadrons after the interaction; in other words, strangeness is conserved in strong interactions.

By defining the strangeness of the K^+ particle to be $+1$ and by applying strangeness conservation to strong interactions that have been observed, it is possible to assign to each hadron a unique value of strangeness. This procedure is of course precisely analogous to the ones used earlier to ascribe a value of charge and baryon number to particles. (Remember, the charge and baryon number of the proton are each defined to be $+1$.)

The values of Q, B and S for the hadrons in Figure 19 are given, with their names and rest masses, in Table 5. (There is no need for you to remember the contents of this Table.)

TABLE 5 Some assorted hadrons (in alphabetical order)

Name	Symbol	Rest mass /(GeV/c^2)	Q	B	S
delta minus	Δ^-	1.232	-1	1	0
delta plus	Δ^+	1.232	1	1	0
delta plus plus	Δ^{++}	1.232	2	1	0
delta zero	Δ^0	1.232	0	1	0
K minus	K^-	0.4937	-1	0	-1
K plus	K^+	0.4937	1	0	1
K zero	K^0	0.4977	0	0	1
K zero bar	$\bar{K}^0$	0.4977	0	0	-1
lambda	Λ	1.116	0	1	-1
neutron	n	0.9396	0	1	0
phi	ϕ	1.020	0	0	0
pi minus	π^-	0.1396	-1	0	0
pi plus	π^+	0.1396	1	0	0
pi zero	π^0	0.1350	0	0	0
proton	p	0.9383	1	1	0
sigma minus	Σ^-	1.197	-1	1	-1
sigma plus	Σ^+	1.189	1	1	-1
sigma zero	Σ^0	1.192	0	1	-1
xi minus	Ξ^-	1.315	-1	1	-2
xi zero	Ξ^0	1.321	0	1	-2

In this Table, each value of rest mass is quoted to four significant figures and each value of charge is given in units of the charge e of the proton.

The introduction of strangeness enables an understanding of why the strong interactions 6a–6d do occur, while the strong interactions 7a–7d do not. In all of the interactions, charge and baryon number are conserved, but only in the interactions 6a–6d is strangeness conserved.

$$\begin{array}{lcccl} & \pi^- + p & \rightarrow & K^+ + \Sigma^- & \\ S & \underbrace{0 \quad 0} & & \underbrace{1 \quad -1} & \\ & 0 & = & 0 & S \text{ conserved} \end{array} \tag{6a}$$

$$\begin{array}{lcccl} & \pi^+ + n & \rightarrow & K^+ + \Sigma^0 & \\ S & \underbrace{0 \quad 0} & & \underbrace{1 \quad -1} & \\ & 0 & = & 0 & S \text{ conserved} \end{array} \tag{6b}$$

$$\begin{array}{lcccl} & K^- + p & \rightarrow & \pi^+ + \Sigma^- & \\ S & \underbrace{-1 \quad 0} & & \underbrace{0 \quad -1} & \\ & -1 & = & -1 & S \text{ conserved} \end{array} \tag{6c}$$

$$\begin{array}{lcccl} & K^- + p & \rightarrow & K^+ + \Xi^- & \\ S & \underbrace{-1 + 0} & & \underbrace{1 \quad -2} & \\ & -1 & = & -1 & S \text{ conserved} \end{array} \tag{6d}$$

$$\begin{array}{lcccl} & \pi^- + p & \not\rightarrow & K^- + \Sigma^+ & \\ S & \underbrace{0 \quad 0} & & \underbrace{-1 \quad -1} & \\ & 0 & \neq & -2 & S \text{ not conserved} \end{array} \tag{7a}$$

$$\begin{array}{lcccl} & \pi^+ + n & \not\rightarrow & \pi^+ + \Lambda & \\ S & \underbrace{0 \quad 0} & & \underbrace{0 \quad -1} & \\ & 0 & \neq & -1 & S \text{ not conserved} \end{array} \tag{7b}$$

$$\begin{array}{lcccl} & K^+ + p & \not\rightarrow & \pi^+ + \Sigma^+ & \\ S & \underbrace{1 \quad 0} & & \underbrace{0 \quad -1} & \\ & 1 & \neq & -1 & S \text{ not conserved} \end{array} \tag{7c}$$

$$\begin{array}{lcccl} & K^- + p & \not\rightarrow & \pi^+ + \Xi^- & \\ S & \underbrace{-1 \quad 0} & & \underbrace{0 \quad -2} & \\ & -1 & \neq & -2 & S \text{ not conserved} \end{array} \tag{7d}$$

By now you may be feeling bewildered by the number of hadrons that you've met in this Section, not to mention the conserved intrinsic properties that have been introduced. Try not to be overwhelmed—the most important point that you need to grasp is that of all the millions of strong interactions that might be predicted to occur, it is found experimentally that the only reactions that are actually observed are those in which charge Q, baryon number B and strangeness S are each conserved. The associated conservation laws tell us which strong interactions will occur and which will not.

What is the physical 'meaning' of baryon number and strangeness? In other words, what is meant by the statement that a hadron has a certain baryon number B and a certain strangeness S? This question is answered similarly to the way in which the question 'What is the meaning of charge?' was answered at the end of Section 4.1. When a hadron is said to have certain values of B and S, statements are implicitly being made about the effect the hadron can have on other particles. The values are labels that allow predictions to be made about whether reactions that involve the hadron are forbidden or not; you have seen several examples of such predictions in this Section.

Finally, we ought to point out that, whereas charge and baryon number are conserved in *all* interactions, strangeness is conserved only in strong and electromagnetic interactions but *not* in weak interactions. There is no need for you to be concerned about this point in this Course.

SAQ 7 By checking to see whether Q, B and S are each conserved, decide which one of the strong interactions (a)–(c) can occur.

(a) $\pi^- + p \rightarrow n + p$

(b) $\Sigma^- + p \rightarrow K^0 + n$

(c) $K^- + p \rightarrow \bar{K}^0 + n$

SAQ 8 The following strong interaction was first observed in 1964 at the Brookhaven laboratory in the USA:

$$K^- + p \rightarrow K^0 + K^+ + X$$

where X is a hadron that had, until then, not be observed.

(a) What is the charge of X, in units of *coulombs*?

(b) Is X a meson or a baryon?

(c) What is the strangeness of X?

4.3 ARE HADRONS FUNDAMENTAL PARTICLES?

You have seen in this Section that hundreds of hadrons have been observed. Are they all fundamental particles, or do they have constituents? This question was addressed in the late 1960s in some crucial experiments that were done at SLAC, in California. These experiments are closely analogous to one carried out at Manchester University by Rutherford's collaborators more than 60 years before, in order to probe the structure of the *atom.*

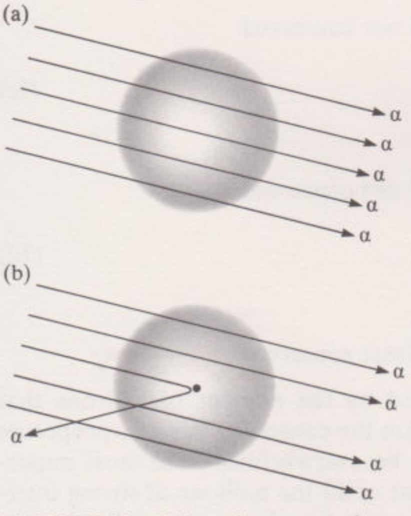


FIGURE 22 Before the α-scattering experiment was done, it was expected that nearly all of the incident α-particles would pass straight through the gold atoms (a), because the atoms were believed to consist of *uniform* distributions of positive and negative charge. However, it was found that a surprisingly high proportion of the α-particles were scattered at large angles (b), and this led Rutherford to suggest (correctly) that atoms each have a nucleus in which their positive charge is concentrated.

Before we consider the SLAC experiments, it is worthwhile to revise briefly the Manchester experiment, which was first discussed in Units 11–12. In this experiment, α-particles (with a de Broglie wavelength of approximately 10^{-15} m) were directed towards a target of gold foil, in order to investigate the structure of the atoms in the target. At the time of the experiment, it was widely believed that the equal amount of positive and negative charge in each atom are both distributed *uniformly*. Calculations based on this idea led to the firm expectation that almost all of the α-particles would pass practically unperturbed through each gold atom (Figure 22a). However, it was found, to the amazement of Ernest Rutherford, that a significant proportion of the incident α-particles were scattered at large angles (see Figure 22b, which bears more than a passing resemblance to the cover of Units 11–12). Rutherford brilliantly used this result to suggest that the positive charge of the atom is concentrated in a tiny core, which he called the nucleus.

The α-scattering experiment therefore enabled the structure of the atom to be probed. The team of experimenters at SLAC used a similar type of experiment to probe the structure of *nuclear* constituents—protons and neutrons.

The team used beams of electrons with energies of approximately 6 GeV, and a corresponding de Broglie wavelength of approximately 10^{-16} m. Note that the wavelength required to probe the contents of a proton or neutron is smaller than the wavelength of approximately 10^{-15} m used in the Manchester experiment to probe the atom. (The wavelengths reflect the sizes of the entities under investigation as you saw in Section 2.)

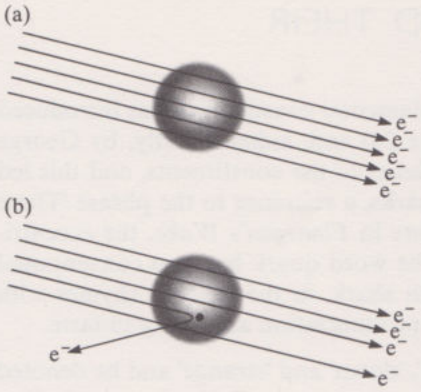


FIGURE 23 The SLAC experiments showed that a surprisingly high proportion of incident electrons are scattered at large angles from protons and neutrons. This evidence supported the idea that protons and neutrons have point-like, charged constituents.

Before the SLAC experiments were done, some physicists visualized the proton and neutron (and other hadrons) as jelly-like particles, with their masses distributed over regions of approximately 10^{-15} m in diameter. In such a visualization, the *charge* of the proton is also distributed over the region that the particle occupies. (The neutron of course has no charge.)

If this picture were correct, the overwhelming majority of the high-energy electrons incident on a proton or neutron would pass through practically unperturbed (Figure 23a). However, the experimenters at SLAC found that a significant proportion of the electrons were scattered through large angles (Figure 23b). Careful interpretations of these data, notably by the American theoretical physicist Richard Feynman, showed that the results of the electron-scattering experiments indicated that *protons and neutrons contain point-like, charged constituents.* This idea was later confirmed by experiments in which protons and neutrons were bombarded by other leptons, and by antileptons.

Because the proton and neutron are in many respects typical hadrons, it was reasonable to extend the conclusion of the Stanford experiments:

> Hadrons are *not* fundamental particles—they *contain* other particles with charge that do appear to be fundamental.

The charged fundamental particles of which hadrons are made will be discussed in the next Section.

SUMMARY OF SECTION 4

1 Hadrons are particles that feel the strong interaction (the interaction that is responsible for the binding together of protons and neutrons in nuclei).

2 Each hadron has an associated value of charge Q, baryon number B and strangeness S.

3 Hadrons that have zero baryon number are known as mesons, those that have baryon number one are known as baryons, and those that have baryon number minus one are known as antibaryons.

4 Charge and baryon number are conserved in all interactions.

5 Strangeness is conserved in strong and electromagnetic interactions but not in weak interactions.

6 Hadrons are not fundamental particles.

SAQ 9 Which of the following types of particle (a)–(c) is currently believed to be fundamental and which are subject to strong interactions? (a) Mesons; (b) baryons; (c) leptons.

5 QUARKS

Several years before the SLAC scattering experiments were performed, it had been suggested that hadrons have fundamental constituents—quarks, and their antiparticles, antiquarks. In this Section, we shall introduce these constituents and show how, according to the simple quark model of hadrons, the charge Q, baryon number B and strangeness S of each hadron are determined by the values of Q, B and S of its constituent quarks and antiquarks. The Section will be concluded by a brief discussion of the interactions of these fundamental hadronic constituents.

QUARK

SIMPLE QUARK MODEL

5.1 THREE QUARKS AND THEIR ANTIPARTICLES

The idea that hadrons might have fundamental constituents was introduced in 1964 by Murray Gell-Mann (Figure 24) and, independently, by George Zweig. They identified three basic varieties of the constituents, and this led Gell-Mann to call them collectively **quarks**, a reference to the phrase 'Three quarks for Muster Mark!' which occurs in *Finnegan's Wake*, the eccentrically written novel by James Joyce. The word quark has two conventional pronunciations—in one it rhymes with shark, in the other it rhymes with pork. Physicists choose their favoured pronunciation according to taste.

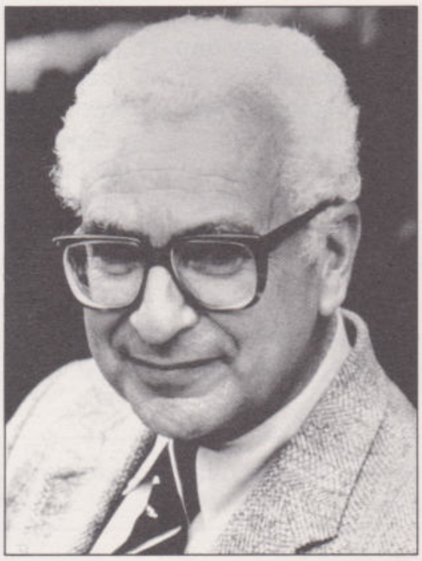


FIGURE 24 Murray Gell-Mann received the 1969 Nobel Prize in physics for 'his contributions and discoveries concerning the classification of elementary particles and their interactions'. Gell-Mann was involved in many of the important steps forward in theoretical particle physics, notably the discovery of the property of strangeness, the formulation of laws concerning the weak interaction, the identification of patterns among the properties of hadrons, and the formulation of the theory of quantum chromodynamics (Section 5.2).

Gell-Mann called the three quarks 'up', 'down' and 'strange' and he denoted them by u, d and s, respectively. As you can see in Table 6, each of these varieties of quark—and their corresponding antiparticles, antiquarks—has a characteristic charge Q, baryon number B, strangeness S and a rest mass that can, however, be given only *approximately* (we shall return to this subject later). Note from Table 6 that, for each variety of quark, its values of Q, B and S are opposite to that of the corresponding antiquark, whereas its rest mass is the same as that of its antiquark. This is just as you should expect from the definition of an antiparticle (Section 3).

TABLE 6 Properties of u, d and s quarks, and of the corresponding antiquarks, $\bar{u}$, $\bar{d}$ and $\bar{s}$

	Charge Q	Baryon number B	Strangeness S	Approximate rest mass/ (GeV/c^2)
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0	0.005
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0	0.01
s	$-\frac{1}{3}$	$+\frac{1}{3}$	-1	0.2
$\bar{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0	0.005
$\bar{d}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0	0.01
$\bar{s}$	$+\frac{1}{3}$	$-\frac{1}{3}$	$+1$	0.2

According to the **simple quark model** of hadrons, each baryon, antibaryon and meson consists of a certain combination of quarks and antiquarks (Figure 25):

(i) Each baryon (i.e. hadron with baryon number 1) consists of three quarks, which may or may not be of the same variety.

(ii) Each meson (i.e. hadron with zero baryon number) consists of a quark and an antiquark, which may or may not be of the same variety.

(iii) Each antibaryon, (i.e. hadron with baryon number -1) consists of three antiquarks, which may or may not be of the same variety.

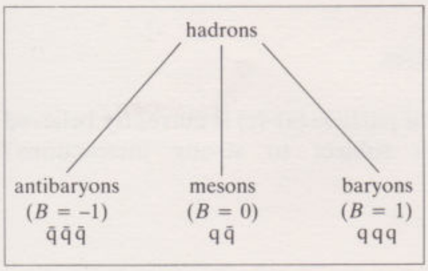


FIGURE 25 Every known hadron can, according to the simple quark model, be interpreted as a combination (with $B = -1$) of three antiquarks, as a combination (with $B = 0$) of a quark and an antiquark or as a combination (with $B = 1$) of three quarks.

The charge of each hadron is simply equal to the *sum* of the charges of its constituent quarks and antiquarks, and the same goes for its baryon number and strangeness.

Consider, for example, the proton, which has charge $+1$, baryon number $+1$ and strangeness 0 (Table 5). These properties are easily accounted for by assuming that the proton consists of two u quarks and one d quark (refer to Table 6 to check the values of Q, B and S for the quarks):

$$\begin{array}{ll} & \mathrm{p} = \mathrm{u} \quad \mathrm{u} \quad \mathrm{d} \\ Q & 1 = \frac{2}{3} + \frac{2}{3} - \frac{1}{3} \\ B & 1 = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} \\ S & 0 = 0 + 0 + 0 \end{array}$$

The corresponding properties of the neutron can also be easily understood if it is assumed to consist of one u quark and two d quarks:

$$\begin{array}{cl} & \mathrm{n} = \mathrm{u} \quad \mathrm{d} \quad \mathrm{d} \\ Q & 0 = \frac{2}{3} - \frac{1}{3} - \frac{1}{3} \\ B & 1 = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} \\ S & 0 = 0 + 0 + 0 \end{array}$$

As two final examples, consider the K^+ and its antiparticle, the K^- (Table 5). The properties of these mesons (which have strangeness $S = +1$ and $S = -1$ respectively) are easily accounted for if they are assumed to be the following quark–antiquark combinations:

$$\begin{array}{cl} & \mathrm{K}^+ = \mathrm{u} \quad \bar{\mathrm{s}} \\ Q & 1 = \frac{2}{3} + \frac{1}{3} \\ B & 0 = \frac{1}{3} - \frac{1}{3} \\ S & 1 = 0 + 1 \end{array} \qquad \begin{array}{cl} & \mathrm{K}^- = \bar{\mathrm{u}} \quad \mathrm{s} \\ Q & -1 = -\frac{2}{3} - \frac{1}{3} \\ B & 0 = -\frac{1}{3} + \frac{1}{3} \\ S & -1 = 0 - 1 \end{array}$$

The simple quark model is not only easy to apply, it is also extremely powerful—the properties of every hadron that has ever been observed can be understood respectively in terms of a three-quark, a three-antiquark or a quark–antiquark combination. Some examples of these combinations (including the ones already discussed here) are collected together for easy reference in Table 7.

Perhaps the most appealing feature of the simple quark model is the remarkable simplification that it introduces into the physics of hadrons. The model enabled the bewildering (and increasing) number of hadrons to be understood in terms of only a few constituents and their antiparticles. You might think that because hadrons can be made from only a small number of varieties of quark, the number of hadrons that can exist should be strictly limited by the possible number of three-quark, three-antiquark and quark-antiquark combinations. However, there is no such limitation, for hadrons with *different* rest masses but with the *same* values of Q, B and S can be made from *the same* combination of quarks and antiquarks. For example, two u quarks and an s quark can form a Σ^+ baryon, with rest mass 1.189 GeV/c^2, or a Σ^{*+} baryon, with rest mass 1.383 GeV/c^2. The Σ^{*+} is merely an excited state of the three quarks:[†] it has the same charge, baryon number and strangeness as the Σ^+; but the rest mass of the Σ^{*+} is higher than that of the Σ^+, because the energy of the uus combination is higher in the Σ^{*+} than it is in the Σ^+.

TABLE 7 Constituents of some hadrons (baryons and mesons), according to the simple quark model

Hadron	Constituents
p	uud
n	udd
Δ^-	ddd
Δ^0	udd
Δ^+	uud
Δ^{++}	uuu
Λ	uds
Σ^-	dds
Σ^0	uds
Σ^+	uus
Ξ^-	dss
Ξ^0	uss
π^+	$\mathrm{u}\bar{\mathrm{d}}$
π^-	$\bar{\mathrm{u}}\mathrm{d}$
π^0	$\mathrm{u}\bar{\mathrm{u}}$ or $\mathrm{d}\bar{\mathrm{d}}$
K^+	$\mathrm{u}\bar{\mathrm{s}}$
K^-	$\bar{\mathrm{u}}\mathrm{s}$
K^0	$\mathrm{d}\bar{\mathrm{s}}$
$\bar{\mathrm{K}}^0$	$\bar{\mathrm{d}}\mathrm{s}$
ϕ	$\mathrm{s}\bar{\mathrm{s}}$

When the simple quark model was suggested, it was clear that the model allowed the charge, baryon number and strangeness of many hadrons to be understood easily. However, the model did have many problems. For example, it certainly could not explain all the experimental observations of the interactions that hadrons undergo. More important, *neither a quark nor an antiquark had been observed in isolation.* Hence, proponents of the model were forced to assume that, for some reason, *quarks and antiquarks can exist only inside hadrons.* To many physicists, this assumption was highly improbable—if hadrons really do contain quarks and antiquarks, why aren't these constituents liberated when hadrons collide at high energies?

[†] You have met this phenomenon before in atomic and nuclear physics. For example, a hydrogen atom consists of an electron and a proton, but it can exist in states of different energy (Units 11–12 and 31). Similarly, atomic nuclei can exist in excited states (Unit 31).

STRONG INTERACTION BETWEEN QUARKS

QUANTUM CHROMODYNAMICS

Bearing in mind these problems, it is perhaps not surprising that the simple quark model was first received by particle physicists with considerable scepticism. Zweig, one of the proponents of the model, has written:

> Getting the CERN report [in which I first put forward the quark model] published was so difficult that I finally gave up trying. When the physics department of a leading University was considering an appointment for me, their senior theorist, one of the most respected spokesmen for all theoretical physics, blocked the appointment at a faculty meeting by passionately arguing that the [quark] model was the work of a 'charlatan'.

To this day, isolated quarks and isolated antiquarks have still not been observed. It is therefore not possible to measure directly their rest masses. Indeed, it is not possible to deduce from the rest masses of hadrons the rest masses of the quarks that they contain. Similarly, it is not possible to calculate the rest mass of a hadron simply by adding the rest masses of the constituents. You can easily check that this is true for each hadron in Table 7, using the data in Tables 5 and 6. For example the rest mass of the proton is $0.9383\,\mathrm{GeV}/c^2$, whereas the total rest mass of its constituent u and d quarks is only $(0.005 + 0.005 + 0.01)\,\mathrm{GeV}/c^2 = 0.02\,\mathrm{GeV}/c^2$.

Ever since the quark model was formulated, the problem of understanding the rest masses of quarks has been an important area of research in theoretical particle physics. Although it is not possible to give precise values for these masses, the values can be quoted approximately. But do remember that the values of the rest masses of quarks that we give are subject to change!

About six years elapsed after Gell-Mann and Zweig's proposal of the idea of quarks and antiquarks before the scientific community accepted that quarks and antiquarks really do exist in hadrons. Some of the most compelling evidence for their existence came from the SLAC experiments, which were described in Section 4. It was found that the data from these (and other) experiments could be easily understood if each proton contains two fundamental particles with charge $+\frac{2}{3}$ and one with charge $-\frac{1}{3}$, and if each neutron contains one fundamental particle with charge $+\frac{2}{3}$ and two with charge $-\frac{1}{3}$ (Figure 26). This, of course, is beautifully in accord with the simple quark model (p = uud, n = udd).

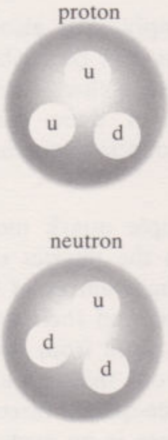


FIGURE 26 According to the simple quark model, a proton consists of two u quarks and one d quark (p = uud) and a neutron consists of one u quark and two d quarks (n = udd).

But why are isolated quarks (and antiquarks) not observed? That question was addressed successfully in the 1970s by theories of quark and antiquark interactions. We shall consider these interactions next.

5.2 THE INTERACTIONS OF QUARKS AND ANTIQUARKS

In common with all electrically charged fundamental particles and antiparticles, quarks and antiquarks have gravitational and electromagnetic interactions. They can also interact weakly, and it is their weak interaction that is responsible for the basic process of β-decay of nuclei (Unit 31). Consider, for example, the basic process of β^--decay:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

which is illustrated schematically in Figure 27. As you can see, in this process a d quark (in the neutron) transmutes into a u quark (in the proton), with the ejection of an electron and electron antineutrino. The laws that describe this transmutation are the same as those that describe the weak interactions of leptons.

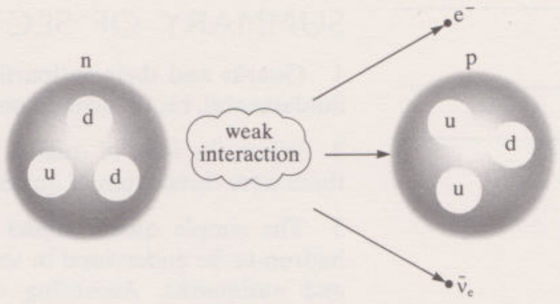


FIGURE 27 At a fundamental level, the β^- decay of a neutron into a proton, an electron and an electron antineutrino $\bar{\nu}_e$ occurs owing to a weak interaction in which a d quark transmutes into a u quark with the emission of an electron and an electron antineutrino ($d \rightarrow u + e^- + \bar{\nu}_e$).

The binding together of quarks (in a baryon), antiquarks (in an antibaryon) and quark–antiquark pairs (in a meson) is due to their *strong* interactions. These interactions really are very strong: the magnitude of the force between two quarks separated by 10^{-15} m is approximately 100 000 N, equivalent to the weight on Earth of ten tonnes (10^4 kg)! Also, these interactions are of very short range, approximately 10^{-15} m.

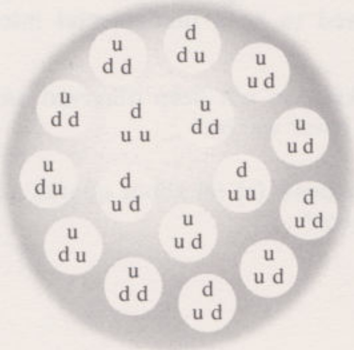


FIGURE 28 A typical nucleus consists of protons and neutrons which, according to the simple quark model, consist of u and d quarks. The interaction between the quarks is believed to be fundamental—it cannot currently be understood in terms of a more basic interaction.

The **strong interaction between quarks** is responsible for the binding of protons and neutrons in atomic nuclei. Each proton and neutron contains quarks that are bound together, and there is a *residual* strong interaction between the protons and neutrons themselves (Figure 28). This residual interaction between protons and neutrons in an atomic nucleus is typical of the strong interaction between hadrons which you met in Section 4, where hadronic collisions were discussed. However, it is important to note that the strong interactions between hadrons are *not* fundamental. (Remember from Section 1 that a fundamental interaction by definition cannot be understood theoretically in terms of a more basic interaction.) It is the strong interaction between the constituent quarks and antiquarks of hadrons that is believed to be truly fundamental: the strong interactions between hadrons are residual to the interactions between their constituent quarks and antiquarks.

In Table 8, the strength and range of the strong interaction between quarks (and antiquarks) are compared with those of the other three fundamental interactions—electromagnetic, weak and gravitational. This Table shows that the strong interaction is considerably stronger than the other types of fundamental interaction.

TABLE 8 Ranges and relative strengths of the four fundamental interactions (order of magnitude estimates)

Type	Range/m	Relative strength*
strong	10^{-15}	10^2
electro-magnetic	∞	1
weak	10^{-18}	10^{-3}
gravit-ational	∞	10^{-36}

* These strengths refer to interactions probed using an energy of 1 GeV. (See the footnote to Table 2 in Section 3.)

The best available theoretical description of the fundamental strong interaction is given by **quantum chromodynamics**, a theory that was formulated in the early 1970s. According to quantum chromodynamics (usually abbreviated to QCD), each particle that participates in fundamental strong interactions has the property 'colour' (hence *chromo*). This property, which has nothing to do with the conventional meaning of colour, plays a role in strong interactions that is analogous to the role played by electrical charge in electromagnetic interactions. Incidentally, it was Gell-Mann who coined the terms quantum chromodynamics and 'colour'.

The QCD theory is extremely complex, so much so that it is difficult in many cases to make detailed predictions about the behaviour of quarks and antiquarks. For example, it is extremely difficult to predict the behaviour of quarks and antiquarks at comparatively large separations (greater than, say, 10^{-14} m). The theory has, however, led physicists to expect that isolated quarks and isolated antiquarks will not be detected, an expectation that (as you saw earlier) is currently in agreement with observation.

If individual quarks and antiquarks were ever detected in isolation, the impact on particle physics would be very considerable, to say the least. Such a discovery would cause theorists to modify their basic ideas of the fundamental strong interaction, and the theory of quantum chromodynamics would almost certainly have to be radically revised. Such disarray among theorists would be a rich prize for experimenters!

LEPTON–QUARK SYMMETRY

CHARM

SUMMARY OF SECTION 5

1 Quarks and their antiparticles (antiquarks) are currently believed to be fundamental, i.e. to have no constituents.

2 When the idea of quarks was first put forward, it was suggested that there were three types of quark—up (u), down (d) and strange (s).

3 The simple quark model of hadrons enables the properties of each hadron to be understood in terms of the properties of its constituent quarks and antiquarks. According to the model, each baryon contains three quarks, each antibaryon contains three antiquarks and each meson contains a quark and an antiquark.

4 Quarks (and antiquarks) each have electromagnetic, weak and gravitational interactions, but it is their strong interactions that are responsible for their being bound together as hadrons. The strong interaction between quarks and antiquarks is currently believed to be a fundamental interaction.

5 Isolated quarks and isolated antiquarks have not been observed and, according to current theoretical ideas, they never will be.

SAQ 10 Which two of the following statements (a)–(e) about quarks and antiquarks are currently believed to be correct?

(a) They have no constituents.

(b) They exist in leptons.

(c) They exist in hadrons.

(d) The only fundamental interaction to which they are subject is the strong interaction.

(e) Their tracks have been observed in drift chambers.

SAQ 11 What is the overall charge, baryon number and strangeness of the hadrons that, according to the simple quark model, have the following constituents? (a) uss; (b) $u\bar{d}$. (Hint: Refer to Table 6.)

6 THE LEPTON–QUARK SYMMETRY

So far, you have met two types of fundamental particle—leptons and quarks—each of which comes in several varieties. The number of varieties of lepton can actually be linked to the number of varieties of quark by the **lepton–quark symmetry**, according to which

> The number of pairs of leptons (one with charge -1, the other with charge 0) is equal to the number of pairs of quarks (one with charge $+\frac{2}{3}$, the other with charge $-\frac{1}{3}$).

This symmetry implies that *the number of varieties of lepton is equal to the number of varieties of quark*. The equality of the two numbers is not only aesthetically pleasing, it also has profound theoretical implications: it was realized in the early 1970s that the lepton–quark symmetry is essential in order to ensure that the widely accepted (and very successful) theory of weak and electromagnetic interactions (Section 7) is physically reasonable. If the symmetry did not exist, then the theory would have to be considerably modified!

We shall show in this Section that the lepton–quark symmetry enabled four new varieties of fundamental particle to be predicted, and we shall compare these predictions with experiment in order to check their validity. You will see in following this discussion that it has proved necessary to introduce some new intrinsic properties of hadrons, notably 'charm'.

6.1 PHYSICISTS DISCOVER CHARM

You have already seen that the four leptons that you met in Section 3—the electron e^-, the mu minus μ^- and their associated neutrinos ν_e and ν_μ—can be grouped together:

$$\begin{pmatrix} e^- & \mu^- \\ \nu_e & \nu_\mu \end{pmatrix} \begin{matrix} \leftarrow & Q = -1 \\ \leftarrow & Q = 0 \end{matrix}$$

where we have indicated the charge Q of the particles in each of the two horizontal rows. Also, you have just seen in Section 5 that Gell-Mann and Zweig proposed the existence of *three* quarks—u, d and s. These fundamental particles can also be grouped together:

$$\begin{pmatrix} u & \\ d & s \end{pmatrix} \begin{matrix} \leftarrow & Q = +\frac{2}{3} \\ \leftarrow & Q = -\frac{1}{3} \end{matrix}$$

It is easy to see that, in order to ensure that there is a lepton–quark symmetry, there should exist another quark that has charge $+\frac{2}{3}$. The existence of such a fourth quark was first suggested (two years before the idea of the lepton–quark symmetry was put forward!) by the American physicist Sheldon Lee Glashow and his European collaborators John Iliopoulos and Luciano Maiani. They suggested, on the basis of a number of complex theoretical arguments, that the new quark should have a property that is analogous to strangeness in the sense that it should be conserved in strong and electromagnetic interactions, but not in weak interactions. This property is called **charm**, and the new quark is therefore referred to as the c quark. In Table 9, its predicted properties are compared with the corresponding properties of the u, d and s quarks.

TABLE 9 Properties of the u, d and s quarks, and the predicted properties of the c quark

Type of quark	Charge Q	Baryon number B	Strangeness S	Charm C	Approximate rest mass /(GeV/c^2)
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0	0	0.005
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0	0	0.01
s	$-\frac{1}{3}$	$+\frac{1}{3}$	-1	0	0.2
c	$+\frac{2}{3}$	$+\frac{1}{3}$	0	1	1.5

ITQ 5 Refer to Table 9. What were the predicted values of the charge, baryon number, strangeness, charm and rest mass of the $\bar{c}$ antiquark?

The symmetry between the four quarks and the four leptons

$$\begin{pmatrix} u & c \\ d & s \end{pmatrix} \quad \begin{pmatrix} e^- & \mu^- \\ \nu_e & \nu_\mu \end{pmatrix}$$

is appealing (and theoretically essential), but it could not be said to have been realized in nature until the existence of the c quark had been confirmed *experimentally*.

Ten years after the new quark was postulated, there was no evidence whatsoever for hadrons that appeared to contain it. However, in the early 1970s, most particle physicists became increasingly convinced that charm (an essential ingredient in their theories of the fundamental interactions) would be observed. A group of theoreticians was even able to predict that charmed hadrons would be observed with rest masses around 3 GeV/c^2. However, there was considerable debate about which type of reaction would give experimenters the best chance of finding these particles.

By the autumn of 1974, the idea of charm was well established in theoretical terms, but it had no direct support from the results of experiments. Then, on 11 November 1974, a remarkable announcement came from the USA.

Two teams of experimenters, one working at SLAC in California, the other at the Brookhaven accelerator near New York, reported that they had independently observed a new particle with truly extraordinary properties. Its rest mass, approximately 3.1 GeV/c^2, was greater than that of any other particle, and it lived about 2 000 times as long as most hadrons!

The Brookhaven team (Figure 29) discovered the particle, which they called the J, in a fixed-target experiment that involved the collision of high-energy protons with the nuclei in a stationary beryllium target. Three thousand miles away, the SLAC team (Figure 30) discovered the particle, which they called the ψ (pronounced psi, rhyming with eye), in a colliding-beam experiment in which electrons collide with positrons in an electronic detector (Figure 31). In order to avoid giving the particle two names, J and ψ, it is usually called the J/ψ (pronounced jay-psi or, sometimes, gypsy!)

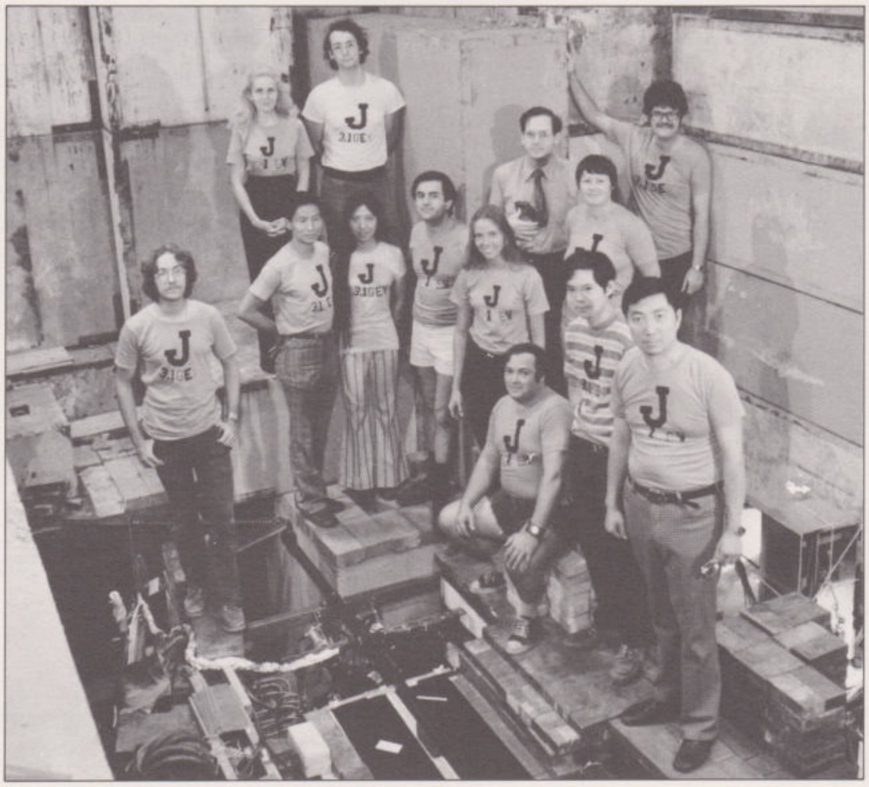
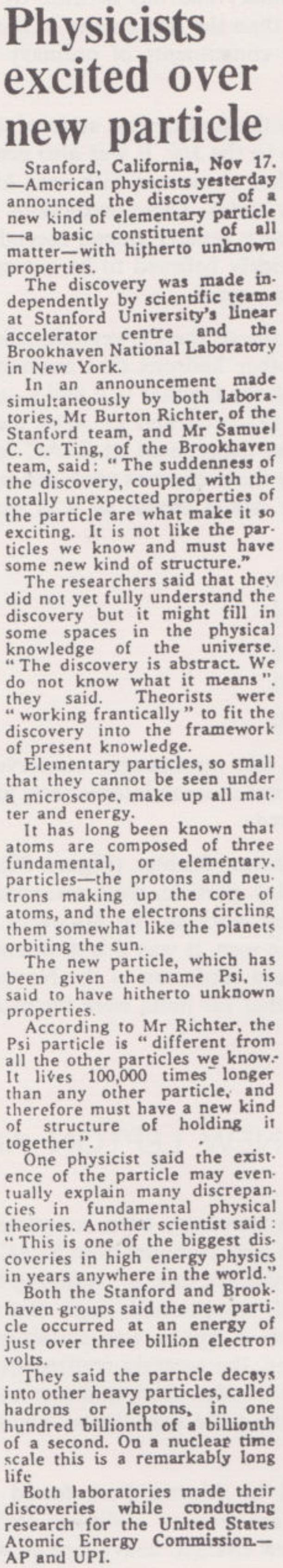


FIGURE 29 Samuel Ting (at the bottom of the photograph on the far right) and the team of physicists (from the Massachusetts Institute of Technology) that discovered the J/ψ at the Brookhaven laboratory.

Ten days later, the SLAC team discovered in their e^+e^- experiment another heavy, electrically neutral particle, the ψ' (pronounced psi prime), with a rest mass of approximately 3.695 GeV/c^2. The team subsequently went on to study in detail the properties of the new particles. They found that the ψ and the ψ' are both mesons (hadrons with zero baryon number) with zero strangeness and zero charm. These properties were subsequently confirmed by experimenters at other accelerators.

The discovery of the new particles, particularly the J/ψ, caused pandemonium among high-energy physicists, who now refer to this dramatic phase in the development of their subject as the November Revolution. News of the upheaval even spread to the world outside (Figure 32)!

The central question that had to be answered was: How can the extraordinary properties of the new particles be understood? This problem was addressed in hundreds of scientific papers, many of which involved hurriedly formulated theories and ideas that now appear to be somewhat bizarre. For example, it was suggested that the J/ψ could be a gauge boson or a hitherto undetected type of particle that consists of a baryon–antibaryon pair. Although these ideas were plausible when they were proposed (a few days after the J/ψ was discovered), physicists soon discarded them when it was realized that their predictions did not agree with experiment.



Physicists excited over new particle

Stanford, California, Nov 17. —American physicists yesterday announced the discovery of a new kind of elementary particle —a basic constituent of all matter—with hitherto unknown properties.

The discovery was made independently by scientific teams at Stanford University's linear accelerator centre and the Brookhaven National Laboratory in New York.

In an announcement made simultaneously by both laboratories, Mr Burton Richter, of the Stanford team, and Mr Samuel C. C. Ting, of the Brookhaven team, said: "The suddenness of the discovery, coupled with the totally unexpected properties of the particle are what make it so exciting. It is not like the particles we know and must have some new kind of structure."

The researchers said that they did not yet fully understand the discovery but it might fill in some spaces in the physical knowledge of the universe. "The discovery is abstract. We do not know what it means". they said. Theorists were "working frantically" to fit the discovery into the framework of present knowledge.

Elementary particles, so small that they cannot be seen under a microscope, make up all matter and energy.

It has long been known that atoms are composed of three fundamental, or elementary. particles—the protons and neutrons making up the core of atoms, and the electrons circling them somewhat like the planets orbiting the sun.

The new particle, which has been given the name Psi, is said to have hitherto unknown properties.

According to Mr Richter, the Psi particle is "different from all the other particles we know. It lives 100,000 times longer than any other particle, and therefore must have a new kind of structure of holding it together".

One physicist said the existence of the particle may eventually explain many discrepancies in fundamental physical theories. Another scientist said: "This is one of the biggest discoveries in high energy physics in years anywhere in the world."

Both the Stanford and Brookhaven groups said the new particle occurred at an energy of just over three billion electron volts.

They said the particle decays into other heavy particles, called hadrons or leptons, in one hundred billionth of a billionth of a second. On a nuclear time scale this is a remarkably long life

Both laboratories made their discoveries while conducting research for the United States Atomic Energy Commission.—AP and UPI.

FIGURE 32 This article, published on the front page of *The Times*, reflects the excitement caused by the discovery of the J/ψ but it contains several errors. One concerns the date of the discovery—it was announced on 11 November, not on 16 November as the text implies. How many errors of physics can you spot?

FIGURE 30 Burton Richter (centre) led the team of physicists from SLAC and the Lawrence Berkeley laboratory that discovered the J/ψ at SLAC. This photograph was taken on 10 November 1974 soon after the discovery of the J/ψ.

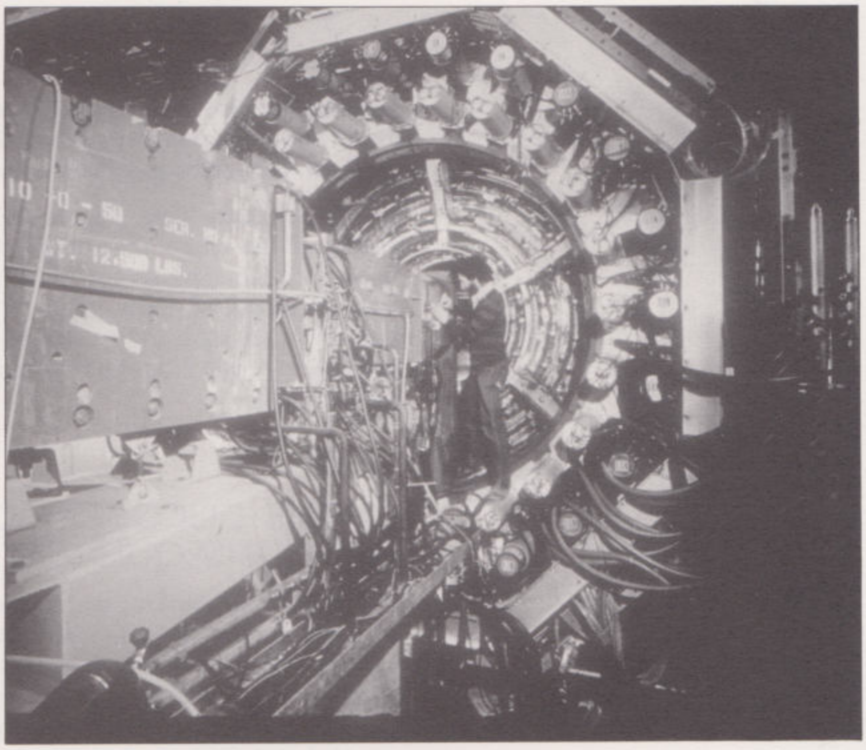


FIGURE 31 The J/ψ was discovered at SLAC using this detector.

The most popular theory of the J/ψ was based on quantum chromodynamics and on the idea that the meson contained a c (charm) quark and a c̄ antiquark:

$$\begin{array}{lcl}
 & J/\psi & c \quad \bar{c} \\
Q & 0 & = \frac{2}{3} - \frac{2}{3} \\
B & 0 & = \frac{1}{3} - \frac{1}{3} \\
S & 0 & = 0 + 0 \\
C & 0 & = 1 - 1
\end{array}$$

Hence, according to the $c\bar{c}$ theory of the J/ψ, the particle has hidden charm—the charm of its c quark cancels that of its c̄ antiquark, giving the J/ψ zero net charm. Also, the $c\bar{c}$ theory said that the rest mass of the parti-

NAKED CHARM

cle is very high compared with that of ordinary hadrons because the rest mass of the c quark is considerably greater than the rest masses of the u, d and s quarks (and their antiparticles), the constituents of ordinary hadrons*.

According to the $c\bar{c}$ theory, the ψ' is simply the first excited state of the $c\bar{c}$ pair, whose lowest energy state corresponds to the J/ψ. It was also predicted using the theory that there should be other $c\bar{c}$ mesons with even higher rest masses, corresponding to higher-energy states. These predictions were soon verified experimentally and the $c\bar{c}$ theory rapidly gained ascendancy over its rivals. Indeed, the $c\bar{c}$ theory was widely believed to be correct by the spring of 1975, and it is now universally accepted.

Any lingering doubts about the validity of the $c\bar{c}$ theory were dispelled in 1975 and 1976 by the discoveries of the other hadrons that contained c quarks (or $\bar{c}$ antiquarks) in combination with the familiar u, d and s quarks (and their antiparticles). For example, the $D^+ = c\bar{d}$ and $D^0 = c\bar{u}$ mesons were discovered in an e^+e^- colliding beam experiment at SLAC in the summer of 1976. These mesons had precisely the properties predicted by the quark model, notably non-zero charm, or **naked charm** as it is usually called:

$$\begin{array}{llll} & D^+ & = c & \bar{d} \\ Q & 1 & = \frac{2}{3} + \frac{1}{3} & \\ B & 0 & = \frac{1}{3} - \frac{1}{3} & \\ S & 0 & = 0 + 0 & \\ C & 1 & = 1 + 0 & \end{array} \qquad \begin{array}{llll} & D^0 & = c & \bar{u} \\ Q & 0 & = \frac{2}{3} - \frac{2}{3} & \\ B & 0 & = \frac{1}{3} - \frac{1}{3} & \\ S & 0 & = 0 + 0 & \\ C & 1 & = 1 + 0 & \end{array}$$

Experiments also showed that charm was, like strangeness, conserved in strong and electromagnetic interactions but not in weak interactions, just as Glashow, Iliopoulos and Maiani had predicted.

In 1976, Samuel Ting (Figure 29) and Burton Richter (Figure 30), the leaders of the teams that discovered the J/ψ particle, were awarded the Nobel Prize in physics for 'their pioneering work in the discovery of a heavy [hadron] of a new kind'. As you have seen, it was this monumental discovery that sparked off the excitement and confusion of the November Revolution—only later did it become clear that the junta were the proponents of charm.

6.2 THE DISCOVERY OF A NEW LEPTON AND THE CONSEQUENCES

No sooner had the four-quark, four-lepton symmetry been completed by the discovery of the charm quark, than there were rumours from SLAC that a group of experimenters there had found evidence in e^+e^- colliding-beam experiments for a new, charged lepton with exceptionally high rest mass (around $1.8\,\mathrm{GeV}/c^2$). The existence of such a lepton was certainly not expected and, if its discovery were confirmed, the recently realized quark–lepton symmetry would be destroyed. Small wonder, then, that one notable physicist remarked in a seminar that he hoped the new lepton would 'go away'.

The team of experimenters at SLAC, led by Martin Perl, found after months of pains-taking analysis that their data on e^+e^- collisions could be understood only if they were observing a new charged heavy lepton, which they called the τ^- (pronounced tau minus), produced with its antiparticle, the τ^+.

$$e^+ + e^- \rightarrow \tau^+ + \tau^-$$

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* The exceptionally long lifetime of the J/ψ was also explained by the $c\bar{c}$ theory, which predicts that the particle's strong decays are suppressed to a level comparable with electromagnetic decays.

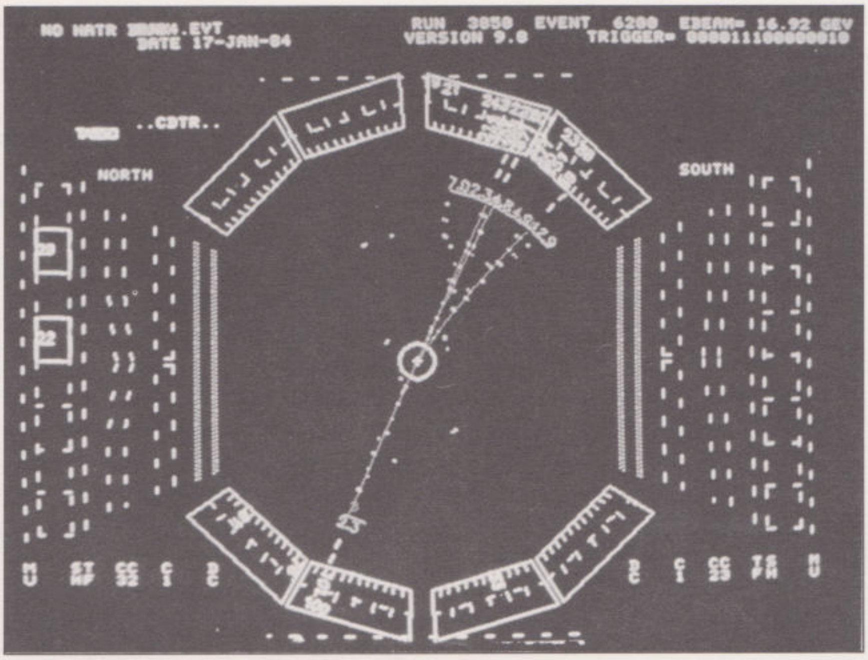
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FIGURE 33 The tracks of the charged particles produced when a τ^+ and a τ^- are produced when an electron and a positron collide. (The collision takes place at the centre of the detector.) The τ^+ decays into a μ^+ (which travels towards the bottom left) and, we believe, into a $\bar{\nu}_\tau$ and a ν_μ (both of which have no charge and therefore do not leave a tell-tale track). The τ^- decays into two π^- particles, a π^+ and, we believe, into a ν_τ, which leaves no track.

For several months, particle physicists were far from certain that the SLAC team really had observed this reaction. One of the main reasons for this scepticism was that the discovery was not confirmed by analyses of e^+e^- collisions at the DESY (pronounced daisy) laboratory in West Germany. However, the DESY group did eventually confirm the discovery in 1975 (Figure 33).

The rest masses of the τ^- and τ^+ have now been pinned down to approximately 1.78 GeV/c^2—roughly 17 times the rest mass of the next heaviest lepton, the μ^-, and roughly 3 500 times the rest mass of the electron!

☐ Does the existence of the τ^- suggest that there exist any more leptons?

■ Yes. It is reasonable to expect that the τ^- should have an associated neutrino ν_τ, with zero charge and zero (or nearly zero) rest mass, just as the electron e^- and mu minus μ^- have associated neutrinos, ν_e and ν_μ respectively, with precisely analogous properties.

☐ What type of interactions do you expect the tau neutrino ν_τ to have?

■ Assuming that the ν_τ has properties that are similar to the other neutrinos (ν_e and ν_μ), you should expect that it has only gravitational and weak interactions. If the particle has zero charge it will not interact electromagnetically. Also, because it is a lepton, it cannot have strong interactions.

By the same reasoning, you should expect the antilepton τ^+ to have an associated antineutrino $\bar{\nu}_\tau$ which has zero charge and zero (or nearly zero) rest mass, and which interacts only gravitationally and weakly.

At the time of writing, neither the ν_τ nor the $\bar{\nu}_\tau$ has been discovered, but that is not at all worrying, as such fundamental particles with only weak and gravitational interactions will be extremely hard to detect. It is, however, expected that experiments will confirm the existence of the ν_τ and $\bar{\nu}_\tau$ during the lifetime of the Course. We shall keep you keep informed in the errata sheets!

TOPNESS

BOTTOMNESS

NAKED BOTTOM

As you will have realized, the τ^- and ν_τ ruined the lepton–quark symmetry:

$$\begin{pmatrix} e^- & \mu^- & \tau^- \\ \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} \quad \begin{pmatrix} u & c & \\ d & s & \end{pmatrix}$$

☐ Can you now predict the existence of two more fundamental particles?

■ It should be plain that the lepton–quark symmetry can be restored (in theory at least) by postulating the existence of two more quarks. This was precisely what was done—the new quarks were called top and bottom (or sometimes truth and beauty). *Enter the symbols* t *and* b *in the gaps above, putting the* t *next to the charm quark* c, *and the* b *next to the strange quark* s.

What could be predicted about the properties of the newly proposed quarks?

ITQ 6 (a) What do you predict to be the charge and baryon number of the t and b quarks? Enter your answers in Table 10.

(b) Is it possible to predict the rest masses of the t and b quarks?

TABLE 10 Properties of six quarks

Type of quark	Charge Q	Baryon number B	Strangeness S	Charm C	Bottomness B	Topness T
u	$+\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
d	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0
c	$+\frac{2}{3}$	$\frac{1}{3}$	0	1	0	0
s	$-\frac{1}{3}$	$\frac{1}{3}$	-1	0	0	0
t			0	0	0	1
b			0	0	-1	0

In Table 10, you can see that the t and b quarks were both predicted to have zero strangeness and charm and that they should each have a characteristic property. The t and b quarks are predicted respectively to have the intrinsic properties of **topness** and **bottomness**. These properties were expected to be analogous to strangeness and charm, in the sense that they should be conserved in strong and electromagnetic interactions, but not in weak interactions.

ITQ 7 (a) What are the predicted charge, baryon number, strangeness, charm, bottomness and topness of the $\bar{t}$ and $\bar{b}$ antiquarks?

(b) What are the predicted rest masses of the $\bar{t}$ and $\bar{b}$ antiquarks in terms of the corresponding rest masses of the t and b quarks?

It is one thing to predict the existence of new quarks, but it is quite another to detect them. Would hadrons that contained t and b quarks (and their antiparticles) be detected?

In the summer of 1977, a group of experimenters at Fermilab (near Chicago) led by the American physicist Leon Lederman, observed a new hadron Υ (pronounced upsilon) which has the extraordinarily high rest mass of approximately 9.5 GeV/c^2, and a remarkably long lifetime compared with ordinary hadrons (ones that have a rest mass of about 1 GeV/c^2: see Figure 19). The properties of the Υ could be understood if it contained a b quark and a $\bar{b}$ antiquark ($\Upsilon = b\bar{b}$). Within two months, the group had detected more hadrons (Υ', Υ'' and Υ''') with even higher rest masses, and these particles were interpreted as excited states of the $b\bar{b}$ pair. This $b\bar{b}$ theory of the new hadrons was soon generally accepted by the high-energy physics community—the b quark (and its antiparticle) had been 'identified', and its rest mass was approximately 5 GeV/c^2.

The discovery of the Υ was not nearly as dramatic as that of the J/ψ. Drama depends considerably on the element of surprise, and whereas in 1974 very few physicists were expecting the $c\bar{c}$ mesons to be discovered, in 1977 many were actually *awaiting* the arrival of the $b\bar{b}$ family! You will not

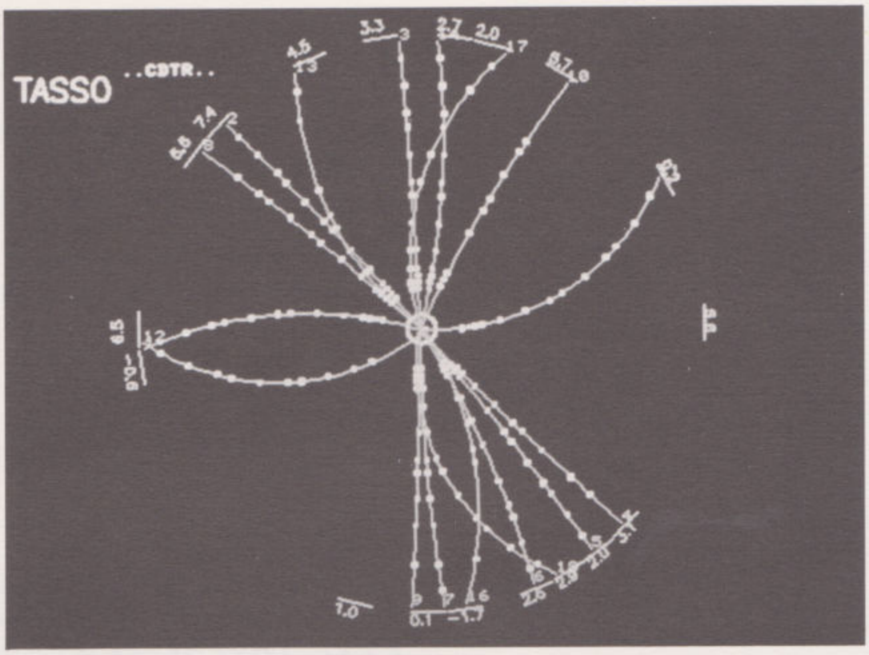

FIGURE 34 The decay of a naked bottom. Note that only the tracks of *charged* particles are observed.

be surprised to learn that hadrons with non-zero bottomness were subsequently observed (Figure 34) with the predicted properties. The observation of these particles, which are sometimes called **naked bottoms**, removed any doubts about the validity of the $b\bar{b}$ theory of the Υ. The analogy with the case of charm is complete.

What about the t quark? At the time of going to print (spring 1988), there is no clear evidence for the existence of hadrons that contain it (or its antiparticle). However, very few physicists doubt that these hadrons will eventually be discovered, such is the confidence in the lepton–quark symmetry.

You may well be wondering if there exist any more leptons and quarks. This is a perfectly valid point. Perhaps the current six lepton–six quark symmetry will one day be ruined by the discovery of an extra lepton or quark?

SUMMARY OF SECTION 6

1 It is essential theoretically that there is a lepton–quark symmetry, according to which the number of pairs of leptons (one with charge -1, the other with charge 0) is equal to the number of pairs of quarks (one with charge $+\frac{2}{3}$, the other with charge $-\frac{1}{3}$).

2 If the lepton–quark symmetry is incomplete, it must be restored by postulating the existence of the missing particle(s). In this way, the symmetry can be used to predict the existence of fundamental particles (leptons and quarks).

3 The identification of the charm quark and its antiparticle as the constituents of the J/ψ particle ($= c\bar{c}$), enabled the four lepton–four quark symmetry to be completed

$$\begin{matrix} Q=-1 & \rightarrow \\ Q=\ \ 0 & \rightarrow \end{matrix} \begin{pmatrix} e^- & \mu^- \\ \nu_e & \nu_\mu \end{pmatrix} \qquad \begin{pmatrix} u & c \\ d & s \end{pmatrix} \begin{matrix} \leftarrow & Q=+\frac{2}{3} \\ \leftarrow & Q=-\frac{1}{3} \end{matrix}$$

4 The unexpected discovery of the τ^- lepton led to the prediction of the ν_τ and also, in order to complete the six lepton–six quark symmetry, to the prediction of two more quarks. These new quarks were called top (t) and bottom (b):

GAUGE BOSONS

PHOTON

INTERMEDIATE VECTOR BOSONS

$$\begin{matrix} Q=-1 \rightarrow \\ Q=\ \ 0 \rightarrow \end{matrix} \begin{pmatrix} e^- & \mu^- & \tau^- \\ \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} \qquad \begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix} \begin{matrix} \leftarrow Q=+\frac{2}{3} \\ \leftarrow Q=-\frac{1}{3} \end{matrix}$$

SAQ 12 Which one of the following entities (a)–(e) is currently believed to have constituents?

(a) J/ψ; (b) τ^-; (c) $\bar{\nu}_\tau$; (d) t; (e) $\bar{b}$.

SAQ 13 What are the charge, baryon number, strangeness, charm, topness and bottomness of the following combinations of quarks and antiquarks?

(a) $c\bar{s}$; (b) $t\bar{u}$.

7 GAUGE BOSONS (TV PROGRAMME)

In this Section, we shall consider the class of fundamental particles known as gauge bosons (pronounced boze-ons). There are four varieties of these particles, each of which is associated with one of the types of fundamental *interaction*. After considering the nature of gauge bosons in general, the four varieties will be considered in turn.

7.1 GAUGE BOSONS—MEDIATORS OF FUNDAMENTAL INTERACTIONS

You have already seen that fundamental particles can interact in four ways—strongly, electromagnetically, weakly and gravitationally. But what is the *mechanism* that underlies these interactions? It is possible to derive some insight into that question using a simple picture based on the idea of *particle exchange*.

An interaction between two fundamental particles can be understood simply in terms of the exchange of another fundamental particle, a **gauge boson** (Figure 35). The interaction is said to be *mediated* by the gauge boson. In order to see how such a mechanism is plausible, picture two ice-skaters on an ice-rink (Figure 36). If skater A throws a ball to skater B, they are propelled *away from* each other, whereas if A throws a boomerang to B, they are propelled *towards* each other. Hence, the skaters' interactions—repulsive or attractive—are 'mediated' by the objects that they exchange. These large-scale situations should give you some intuitive understanding of how fundamental interactions between fundamental particles can be mediated by the exchange of another particle. However, you should not take the 'exchange picture' literally, because it is only an analogy. A complete and rigorous understanding of the role of gauge bosons can be obtained only by using the theories of quantum mechanics and special relativity.

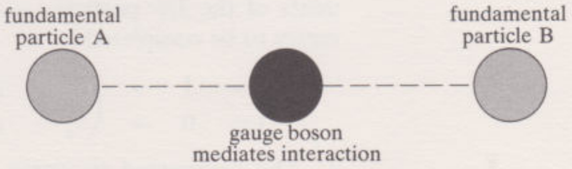

FIGURE 35 Each fundamental interaction between fundamental particles is mediated by a characteristic type of gauge boson.

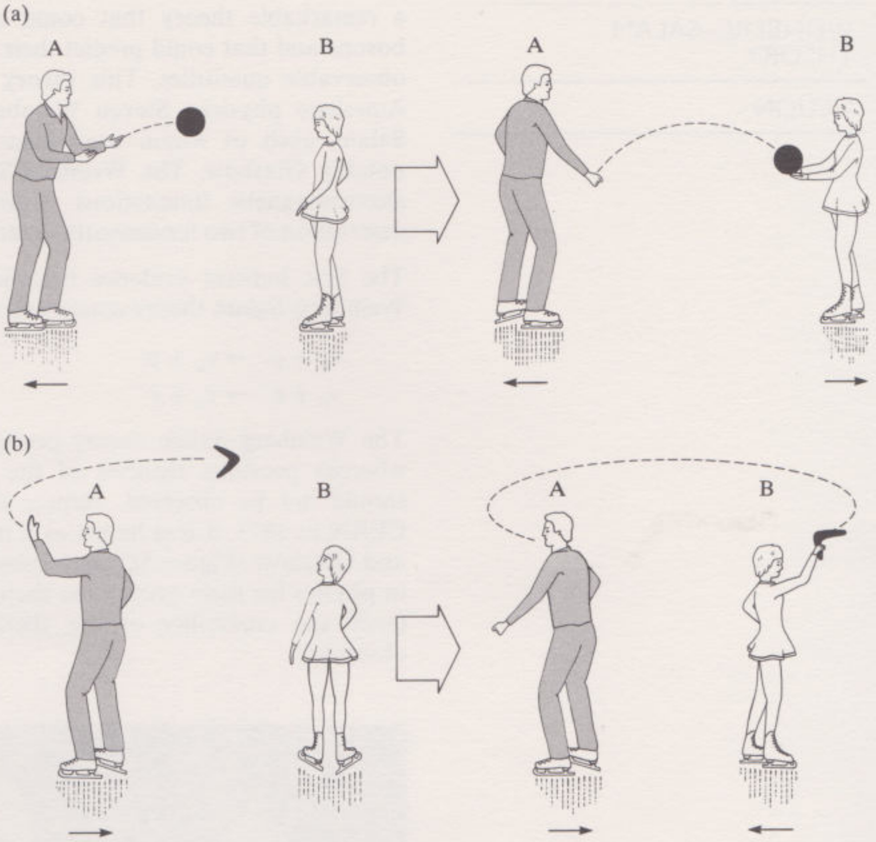

FIGURE 36 Interactions that can occur between two ice-skaters when they exchange (a) a heavy object, (b) a boomerang.

Each type of fundamental interaction is mediated by a characteristic type of gauge boson (Figure 37): electromagnetic interactions are mediated by the photon, weak interactions by intermediate vector bosons, strong interactions by gluons and gravitational interactions by the graviton. Each of these gauge bosons has a characteristic rest mass and electrical charge (and each one has zero values of baryon number, strangeness, charm, topness and bottomness).

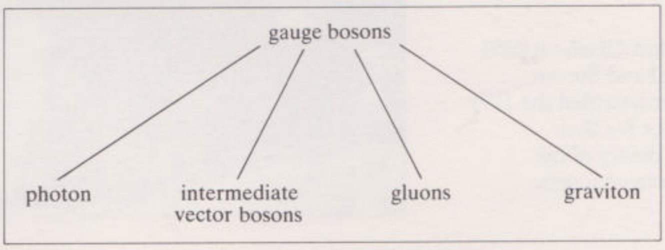

FIGURE 37 The four types of gauge boson.

7.2 TYPES OF GAUGE BOSON

7.2.1 THE PHOTON

The **photon**, normally denoted by the symbol γ, is the fundamental particle that mediates electromagnetic interactions. It is electrically neutral and has zero rest mass.

The photon is its own antiparticle; in other words, the antiparticle of a photon is a photon. Such a fundamental particle is said to be self-conjugate (all neutral gauge bosons are of this type).

7.2.2 INTERMEDIATE VECTOR BOSONS

In the late 1950s, it was suggested that weak interactions are mediated by **intermediate vector bosons**, W^+, W^- and Z, although no theory could describe the properties of the hypothetical particles and there was no evidence whatever for their existence. However, in 1967 there was put forward

WEINBERG–SALAM THEORY

GLUON

a remarkable theory that could describe the behaviour of these gauge bosons and that could predict their masses in terms of other experimentally observable quantities. This theory was formulated independently by the American physicist Steven Weinberg and the Pakistani physicist Abdus Salam, each of whom used ideas that had been developed by others, notably Glashow. The **Weinberg-Salam theory** described both weak and electromagnetic interactions within a single theory—it gave a *unified* description of two fundamental interactions*.

The first indirect evidence that firmly supported the predictions of the Weinberg–Salam theory concerned weak interactions such as

$$\nu_\mu + p \rightarrow \nu_\mu + p$$
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

The Weinberg–Salam theory predicted that these reactions should occur, whereas previous theories of the weak interaction predicted that they should *not* be observed. Hence, when these reactions were observed at CERN in 1973, it was hailed as a triumph for the theory. Weinberg, Salam and Glashow (Figure 38) were subsequently awarded the 1979 Nobel Prize in physics for their work, even though the W^+, W^- and Z—on whose existence the credibility of the theory depended—had not actually been observed!

FIGURE 38 Sheldon Glashow (left), Abdus Salam (centre) and Steven Weinberg (right) were awarded the 1979 Nobel Prize in physics 'for their contributions to the theory of the unified weak and electromagnetic interaction'.

Weinberg and Salam's theory predicted that the rest masses of the intermediate vector bosons are extraordinarily high. It was expected that the rest mass of the W^+ and its antiparticle the W^- should be approximately $80\,\mathrm{GeV}/c^2$, and that the rest mass of the Z should be approximately $90\,\mathrm{GeV}/c^2$. Alas, these predictions could not be checked because the energies available at the particle accelerators at the time were far too low for particles of such high rest masses to be produced.

Most physicists were of the opinion that it would be decades before accelerators of sufficiently high energy would be available to check the predictions. However, Carlo Rubbia, a leading Italian experimenter, believed otherwise. In 1976, he and some collaborators suggested that if the intermediate vector bosons existed and if they had roughly the properties suggested by the Weinberg–Salam theory, then it should just be possible to detect them using CERN's SPS (Super Proton Synchrotron) accelerator (Figure 8). This machine was originally designed to generate 500 GeV protons for fixed-

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* Although the weak and electromagnetic interactions are generally regarded as having been unified by the Weinberg–Salam theory, we shall continue to refer to the two types of interactions as being separate, in order to be consistent with the material earlier in the text.

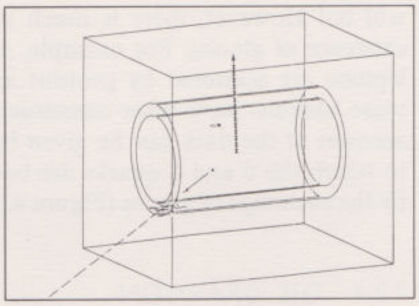

FIGURE 39 As described in the TV programme 'The Search for the W and Z', the existence of W particles was confirmed by the observation of the tell-tale straight tracks of electrons and muons. The track in this record is left by a muon after the decay $W^- \rightarrow \mu^- + \bar{\nu}_\mu$. (The antineutrino does not leave a track because it has no charge.)

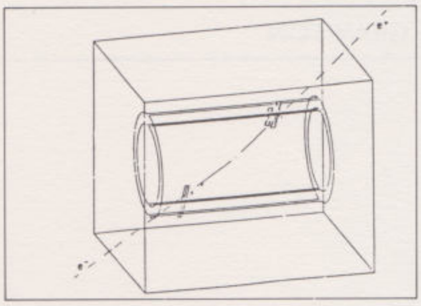

FIGURE 40 As described in the TV programme, the existence of the Z was confirmed by the observation of tell-tale tracks left by e^+e^- (and $\mu^+\mu^-$) decay products of the particle. In this record, the tracks are left by an electron and a positron, $Z \rightarrow e^+ + e^-$. This record, and the one in Figure 39, were obtained using drift chambers.

target experiments, but the energy of these protons was too low to enable intermediate vector bosons to be produced. However, Rubbia and his collaborators proposed that the SPS could be converted into a machine that could be used to do colliding-beam experiments with 270 GeV protons and 270 GeV antiprotons. The conversion was made possible by advances in accelerator technology made by the Dutch physicist Simon van der Meer.

Calculations showed that, if the Weinberg–Salam theory were correct, it should be possible to observe certain types of decay of the intermediate vector bosons, notably

$$W^+ \rightarrow \mu^+ + \nu_\mu$$
$$W^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$Z \rightarrow e^+ + e^-$$

After the proposal had been carefully evaluated, CERN decided to go ahead with the project, even though many physicists firmly believed that the outcome would be an expensive fiasco, with no clear evidence for intermediate vector bosons and an acutely embarrassing loss of kudos for European science. The prestige of CERN was at stake.

The search for the intermediate vector bosons was carried out by two teams, one of which was led by Rubbia, with his characteristic flair and exuberance. In the TV programme 'The search for the W and Z', we follow the progress of Rubbia's team of 135 physicists, from the beginnings of the project to the tentative announcement of the discoveries of the W^+ and W^- in January 1983. The group found that, just as Weinberg and Salam's theory had predicted, the rest masses of the W particles were around $80\,\text{GeV}/c^2$ and that they could decay into a charged lepton and a neutrino (Figure 39). The group later confirmed the existence of the Z (Figure 40), which had precisely the properties expected on the basis of the Weinberg–Salam theory. Few scientists were surprised when the 1984 Nobel Prize for physics was awarded jointly to Carlo Rubbia and Simon van der Meer (Figure 41).

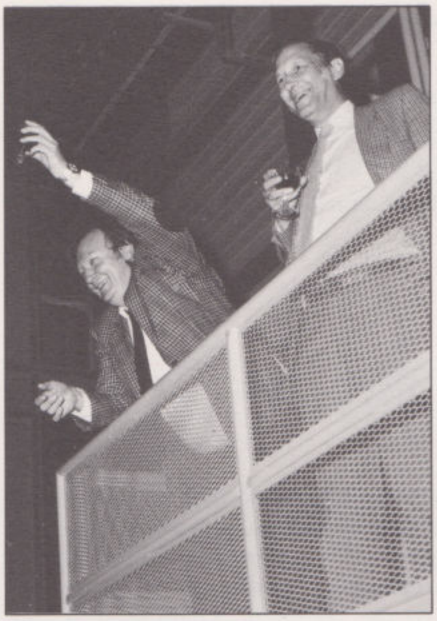

FIGURE 41 Carlo Rubbia (left) and Simon van der Meer (right) were awarded the 1984 Nobel Prize for physics for 'the discovery of the [gauge bosons] W and Z, communicators of the weak interaction'.

7.2.3 GLUONS

The strong interactions between quarks (and antiquarks) are mediated by gauge bosons that Gell-Mann called **gluons**. According to quantum chromodynamics, there are eight different gluons $g_1, g_2, \ldots, g_8$, each of which has 'colour' but zero rest mass and zero electrical charge. Isolated gluons have never been detected and, according to QCD theory, they never will be! However, there is much indirect but compelling evidence for the existence of gluons. For example, data from experiments in which charged leptons are scattered by protons and neutrons can be understood only if these hadrons have other constituents besides u and d quarks. An excellent account of the data can be given by quantum chromodynamics, according to which the u and d quarks are bound together in a proton and a neutron by the exchange of gluons (Figure 42).

GRAVITON

7.2.4 THE GRAVITON

It is believed on theoretical grounds that gravitational interactions are mediated by a gauge boson known as the **graviton**, G. This particle has not yet been observed, but it is predicted to have zero rest mass and zero charge. Experimenters do not expect to be able to detect gravitons in the foreseeable future—they are even more difficult to detect than the intermediate vector bosons! The graviton awaits its Rubbia.

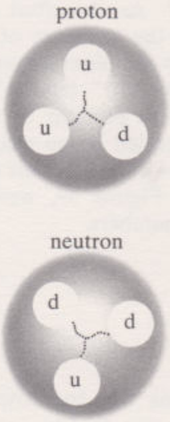

FIGURE 42 In the proton and the neutron, the constituent quarks are bound together by gluons (shown here as wavy dotted lines).

SUMMARY OF SECTION 7

1 Gauge bosons are fundamental particles that mediate fundamental interactions.

2 A characteristic type of gauge boson is associated with each type of fundamental interaction. Electromagnetic interactions are mediated by the photon, weak interactions by intermediate vector bosons, strong interactions by gluons. Gravitational interactions are believed to be mediated by the graviton, although this gauge boson has not yet been detected.

SAQ 14 Which one of the following statements about gauge bosons is correct? Explain your answer.

(a) The photon is not a fundamental particle.

(b) Because the decay $W^+ \rightarrow \mu^+ + \nu_\mu$ has been observed, it can be concluded correctly that the W^+ contains a μ^+ and a ν_μ.

(c) Each proton and neutron in an atomic nucleus contains quarks bound together by gluons.

8 PARTICLE PHYSICS IN PERSPECTIVE

In this Unit, you have seen that it is currently believed that there are three types of fundamental particle—leptons, quarks and gauge bosons. You have also seen that there are four types of fundamental interaction—gravitational, strong, weak and electromagnetic (although the latter two have been described in a unified way by the Weinberg–Salam theory). The fundamental particles are listed in Table 11 with their charges and rest masses.

Through the eyes of a particle physicist, a seemingly uncomplicated scene on Earth has extraordinary richness and complexity. For example, consider, from the particle physicist's point of view, the scene that you met at the beginning of the Unit (Figure 43).

Cosmic rays, which consist ultimately of certain quarks, leptons and gauge bosons, are raining down on the whole scene, and antineutrinos are emerging from the ground (owing to radioactive decay processes within the Earth). All the matter is attracted towards the Earth by gravitational interactions, which are mediated by gravitons. The atomic constituents of the matter in turn consist of electrons and nuclei; the electrons are examples of leptons and the nuclei consist of combinations of u and d quarks. The elec-

TABLE 11 The fundamental particles*

Particle	Symbol	Charge	Rest mass /(GeV/c^2)
LEPTONS			
electron	e^-	-1	5.11×10^{-4}
mu minus	μ^-	-1	1.06×10^{-1}
tau minus	τ^-	-1	1.78
electron neutrino	ν_e	0	≈ 0
muon neutrino	ν_μ	0	≈ 0
tau neutrino	ν_τ?	0	≈ 0
QUARKS			
up	u	$\frac{2}{3}$	≈ 0.005
down	d	$-\frac{1}{3}$	≈ 0.01
charm	c	$\frac{2}{3}$	≈ 1.3
strange	s	$-\frac{1}{3}$	≈ 0.2
top	t?	$\frac{2}{3}$	
bottom	b	$-\frac{1}{3}$	≈ 5
GAUGE BOSONS			
photon	γ	0	0
intermediate vector bosons	W^+	1	82
	W^-	-1	82
	Z	0	93
gluons	$g_1, \ldots, g_8$	0	0
graviton	G?	0	0

* Note that there also exist antileptons and antiquarks (Sections 3 and 5).

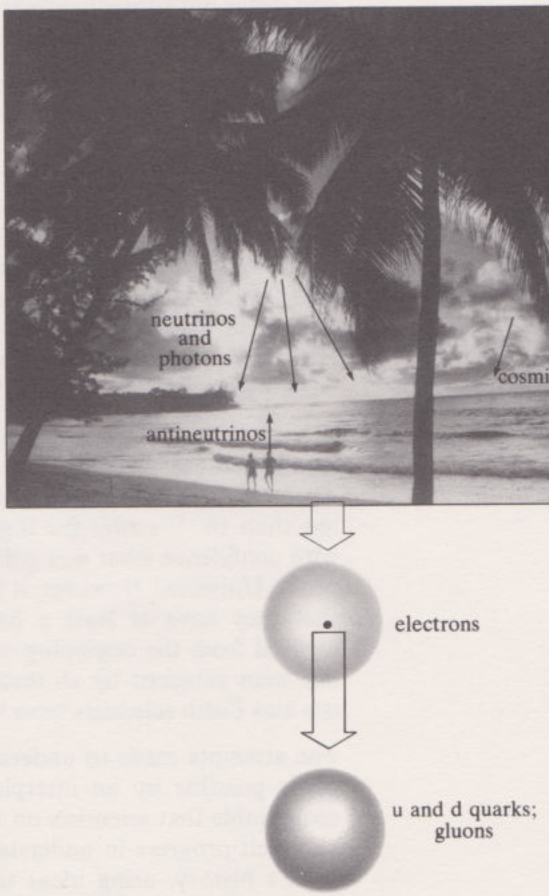

FIGURE 43 A 'fundamental' view of the scene shown in Figure 1.

BIG BANG

trons in an atom are bound to the atom's nucleus by the electromagnetic interaction, and the quarks in the nucleus are held together by the fundamental strong interaction, mediated by gluons. From the Sun, there is raining down both photons (gauge bosons) and neutrinos (leptons).

The formulation of such a qualitative description is not normally the province of particle physicists, who deal mainly in terms of rigorously defined theories of fundamental particles and their interactions. In this Unit, the details of such theories (e.g. quantum chromodynamics and the Weinberg–Salam theory) have been avoided and we have concentrated on the *results* of the theories and on their relevance to the search for fundamental particles. As you have probably gathered, the search is by no means at an end, and many profound questions remain to be answered. For example:

1 *Do there exist more quarks, leptons and gauge bosons*? It is, of course, quite possible that experimenters will detect more of these particles.

2 *Are leptons, quarks and gauge bosons really fundamental*? Perhaps experimenters will show that these types of particle actually have constituents after all?

3 *Is it possible to formulate a single, unified theory that describes all the possible fundamental interactions between all of the fundamental particles*? This is currently one of the central questions of theoretical particle physics. In one line of research that has proved particularly fruitful, it is suggested that the fundamental entities of matter are 'string-like' (i.e. *not* point-like), on a scale of 10^{-35} m. This idea will be hard to test because present experiments probe the structure of matter down to the comparatively huge scale of 10^{-18} m!

One of the most exciting topics in contemporary science concerns the application of the fundamental laws of physics to the evolution of the Universe. Using these laws in conjunction with a wealth of astronomical data, it has been established (to the satisfaction of most scientists) that the Universe began in an event known as the **Big Bang**. In this event, which is believed to have occurred approximately 16 000 million years ago, space, time, matter and energy were actually created. At first, the Universe was extremely hot and dense but subsequently it expanded and cooled.

Some of the highlights in the evolution of the Universe (according to current theories) are shown in Figure 44. As you can see from this Figure, approximately 10^{-35} seconds after the Big Bang the Universe contained leptons, quarks and gauge bosons (and their antiparticles), moving around with extremely high energy. Within about a thousandth of a second, the quarks and antiquarks cooled sufficiently to form hadrons. After about a minute, the energies of protons and neutrons were sufficiently low that they could 'stick together' to form atomic nuclei, but it was not until about 10 000 years later that the energies of electrons and nuclei were low enough for stable chemical elements to be formed. On the cosmic timescale of Figure 44, terrestrial rocks were formed quite recently and life on Earth began 'yesterday', so to speak!

The evolution of the Universe certainly cannot be said to be fully understood, because there are many stages of the process that remain unclear. There is some doubt about the details of the processes going on at times less than 10^{-12} s after the Big Bang, and even physicists do not dare to say with confidence what was going on much before 10^{-35} s after the beginning of the Universe! However, it is fair to say that scientists are now confident that they have at least a basic understanding of how the Universe has evolved from the beginning of time to the present day. This understanding has been achieved by an interdisciplinary collaboration—biologists, chemists and Earth scientists have been involved, as well as physicists.

The attempts made to understand the evolution of the Universe have been made possible by an interplay of scientific theory and experiment. It is remarkable that scientists on Earth, a mere speck in the cosmos, have made so much progress in understanding 16 000 million years or so of the Universe's history, using ideas that have been developed (for the most part) temperature falling

Time after Big Bang	Event
0	Big Bang
10^{-35} s	Universe consists of quarks, leptons, gauge bosons (and their antiparticles)
10^{-3} s	Hadrons formed from quarks and from antiquarks
1 minute	Lightest nuclei formed from protons and neutrons
10 000 years	Atoms formed from electrons and nuclei
11 400 Ma	Planets in Solar System formed
11 800 Ma	Oldest terrestrial rocks formed; continental drift
12 600 Ma	Prokaryotes appeared
15 000 Ma	Eukaryotes appeared
15 600 Ma	Early land plants and fish appeared
15 700 Ma	First ferns appeared
15 850 Ma	Dinosaurs roamed
15 950 Ma	First mammals appeared
16 000 Ma	*Homo sapiens* first walked the Earth (about 4 Ma ago)

FIGURE 44 Some notable events since the Big Bang. In this Figure, it is assumed in the nine lowest entries that *Homo sapiens* first walked the Earth 16 000 million years after the Big Bang. However, this figure has actually been determined only to within an uncertainty of several thousand million years, so the preceding eight entries have the same uncertainty!

only in the last 100 years. This progress is surely one of the greatest scientific achievements of the 20th century. As Steven Weinberg has reflected in his book about the origin of the Universe:

> Men and women are not content to comfort themselves with tales of gods and giants, or to confine their thoughts to the daily affairs of life; they also build telescopes and satellites and accelerators, and sit at their desks for endless hours working out the meaning of the data they gather. The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy.
>
> (Epilogue to *The First Three Minutes*)

FURTHER READING

Particles and Fields (1980), W. H. Freeman and Company. This is a collection of key articles on particle physics that have been published between 1953 and 1979 in *Scientific American*, an excellent source of articles on new developments in the subject. The article by Glashow on quantum chromodynamics is particularly strongly recommended.

Close, F., Marten, M. and Sutton, C. (1987) *The Particle Explosion*, Oxford University Press. A beautifully illustrated and easy-to-read survey of the world of particle physics.

Parker, B. (1987) *Search for a Supertheory: From Atoms to Superstrings*, Plenum. A fairly advanced text that gives a clear account of the developments that have led to the formulation of 'string' theories.

Sutton, C. (ed.) (1985) *Building the Universe*, Blackwell and New Scientist. This is a selection of *New Scientist* articles on particle physics, linked by helpful explanatory passages by the editor.

Watkins, P. (1986) *The Story of the W and Z*, Cambridge University Press. A readable account of the discovery of the intermediate vector bosons, with much useful background material, written at an elementary level.

Weinberg, S. (1977) *The First Three Minutes*, André Deutsch. A popular account of the physics of the Big Bang, written by one of the outstanding theoreticians of recent times.

OBJECTIVES FOR UNIT 32

After you have worked through this Unit, you should be able to:

1 Explain the meaning of, and use correctly, all the terms flagged in the text.

2 Recall that leptons, quarks and gauge bosons are currently believed to be fundamental particles. (*SAQs 1, 5, 9, 10, 12 and 14*)

3 State the rest mass, charge, baryon number etc. of an antiparticle, given the corresponding properties of the corresponding particle. (*ITQs 1, 5 and 7, SAQ 5*)

4 Convert from units of kilograms to units of GeV/c^2 and from units of joules to units of GeV. (*SAQs 3 and 4*)

5 Apply the basic principles that underlie the operation of particle accelerators and detectors. (*SAQs 2–4*)

6 Recall the properties and interactions of leptons. (*ITQ 2, SAQs 5, 6 and 9*)

7 Apply the conservation laws of charge, baryon number, strangeness, charm, topness and bottomness to examples of strong interactions. (*ITQs 3 and 4, SAQs 7 and 8*)

8 Recall the four types of interaction that are currently believed to be fundamental. (*SAQ 10*)

9 Apply the simple quark model. (*SAQs 11 and 13*)

10 State the consequences of a breakdown of the lepton–quark symmetry. (*ITQs 6 and 7*)

11 Describe the role played by gauge bosons in mediating fundamental interactions. (*SAQ 14*)

ITQ ANSWERS AND COMMENTS

ITQ 1 The positron e^+ has charge $+1$ (in units of the proton's charge e) and rest mass $5.11 \times 10^{-4}\,\mathrm{GeV}/c^2$, the mu plus μ^+ has charge $+1$ and rest mass $1.06 \times 10^{-1}\,\mathrm{GeV}/c^2$; both antineutrinos $\bar{\nu}_e$ and $\bar{\nu}_\mu$ have zero charge and zero (or nearly zero) rest mass. The properties follow from the definition of antiparticle: an antiparticle has the *opposite* charge but the *same* rest mass as the corresponding particle.

ITQ 2 The charged leptons and antileptons (e^-, e^+, μ^- and μ^+) can interact electromagnetically because they have charge, and they can interact gravitationally, in common with all other particles and antiparticles. By the same token, neutrinos and antineutrinos can also interact gravitationally.

ITQ 3 Reaction (c) is forbidden:

$$\text{(c)}\qquad \mathrm{p} + \mathrm{p} \not\to \mathrm{p} + \mathrm{p} + \pi^+ + \pi^- + \pi^+$$

$$Q\quad \underbrace{+1\quad +1}_{+2} \quad\neq\quad \underbrace{+1\quad +1\quad +1\quad -1\quad +1}_{+3} \qquad Q\text{ not conserved}$$

Reactions (a) and (b) are allowed, according to charge conservation:

$$\text{(a)}\qquad \mathrm{p} + \mathrm{p} \to \mathrm{p} + \mathrm{p}$$

$$Q\quad \underbrace{+1\quad +1}_{+2} \quad=\quad \underbrace{+1\quad +1}_{+2} \qquad Q\text{ conserved}$$

$$\text{(b)}\qquad \mathrm{p} + \mathrm{p} \to \mathrm{p} + \mathrm{p} + \pi^+ + \pi^-$$

$$Q\quad \underbrace{+1\quad +1}_{+2} \quad=\quad \underbrace{+1\quad +1\quad +1\quad -1}_{+2} \qquad Q\text{ conserved}$$

ITQ 4 Reaction (b) is forbidden because baryon number is not conserved:

$$\text{(b)}\qquad \mathrm{p} + \mathrm{p} \not\to \pi^+ + \mathrm{p} + \mathrm{n} + \mathrm{n}$$

$$B\quad \underbrace{1\quad 1}_{2} \quad\neq\quad \underbrace{0\quad 1\quad 1\quad 1}_{3} \qquad B\text{ not conserved}$$

In reactions (a) and (c), baryon number and charge are both conserved, so neither reaction is forbidden:

$$\text{(a)}\qquad \mathrm{p} + \mathrm{p} \to \pi^+ + \mathrm{p} + \mathrm{n}$$

$$Q\quad \underbrace{1\quad 1}_{2} \quad=\quad \underbrace{1\quad 1\quad 0}_{2} \qquad Q\text{ conserved}$$

$$B\quad \underbrace{1\quad 1}_{2} \quad=\quad \underbrace{0\quad 1\quad 1}_{2} \qquad B\text{ conserved}$$

$$\text{(c)}\qquad \mathrm{p} + \mathrm{p} \to \mathrm{p} + \mathrm{p} + \pi^0 + \pi^0$$

$$Q\quad \underbrace{1\quad 1}_{2} \quad=\quad \underbrace{1\quad 1\quad 0\quad 0}_{2} \qquad Q\text{ conserved}$$

$$B\quad \underbrace{1\quad 1}_{2} \quad=\quad \underbrace{1\quad 1\quad 0\quad 0}_{2} \qquad B\text{ conserved}$$

ITQ 5 The $\bar{c}$ antiquark should have charge $-\frac{2}{3}$, baryon number $-\frac{1}{3}$, strangeness 0, charm -1 and a rest mass of approximately $1.5\,\text{GeV}/c^2$. These properties follow from the definition of an antiparticle: an antiparticle has the *opposite* charge, baryon number, strangeness and charm, but the *same* rest mass as the corresponding particle.

ITQ 6 (a) The t and b quarks should, in common with the other quarks, have baryon number $\frac{1}{3}$. The t quark should, in common with the u and c quarks, have charge $+\frac{2}{3}$, whereas the b quark should, in common with the d and s quarks, have charge $-\frac{1}{3}$.

(b) No, you should not be able to predict the rest masses of the t and b quarks. We certainly have not shown in the text how such predictions could be made!

ITQ 7 (a) For the $\bar{t}$ antiquark: $Q = -\frac{2}{3}$, $B = -\frac{1}{3}$, $C = 0$, $\mathsf{B} = 0$, $T = -1$. For the $\bar{b}$ antiquark $Q = +\frac{1}{3}$, $B = -\frac{1}{3}$, $C = 0$, $\mathsf{B} = 1$, $T = 0$. These values are opposite to those of the corresponding quarks.

(b) The rest mass of the $\bar{t}$ should be the same as that of the t, and the rest mass of the $\bar{b}$ should be the same as that of the b. Remember, the rest mass of an antiparticle is the same as that of the corresponding particle.

SAQ ANSWERS AND COMMENTS

SAQ 1 None, because each of the entities has constituents. A chlorine molecule consists of chlorine atoms; a helium atom consists of a helium nucleus and two electrons; a uranium nucleus consists of protons and neutrons.

SAQ 2 Other particles can be produced 'out of thin air' when two particles collide because some of the total kinetic energy of the original particles can be converted into the energy of the rest masses of the produced particles. Energy is, as always, conserved:

energy equiv. to total rest mass of particles before the collision	+	kinetic energy of particles before the collision	=	energy equiv. to total rest mass of particles after the collision	+	kinetic energy of particles after the collision

SAQ 3 (a) No, because the π^0 has no charge. Only charged particles can leave a track in a drift chamber.

(b) No. According to the special theory of relativity, the speed of a particle can never exceed the speed of light in a vacuum, $c \approx 3 \times 10^8\,\text{m}\,\text{s}^{-1}$.

(c) $0.14\,\text{GeV}/c^2$.

On the back cover of these Units, it is stated that $1\,\text{GeV}/c^2 \approx 1.783 \times 10^{-27}\,\text{kg}$.

$$\text{Hence, } 1\,\text{kg} \approx \frac{1}{1.783 \times 10^{-27}}\,\text{GeV}/c^2$$

$$\text{i.e.}\quad 1\,\text{kg} \approx 5.61 \times 10^{26}\,\text{GeV}/c^2$$

The rest mass of the π^0 is $2.41 \times 10^{-28}\,\text{kg}$

$$\approx 2.41 \times 10^{-28}\,\text{kg} \times (5.61 \times 10^{26}\,\text{kg}^{-1}\,\text{GeV}/c^2)$$
$$\approx 0.14\,\text{GeV}/c^2$$

SAQ 4 (a) (i) 540 GeV, (ii) $8.6 \times 10^{-8}\,\text{J}$.

(i) The total kinetic energy of the two particles is $270\,\text{GeV} + 270\,\text{GeV} = 540\,\text{GeV}$.

(ii) Because $1\,\text{GeV} = 10^9\,\text{eV} \times (1.60 \times 10^{-19}\,\text{J}\,\text{eV}^{-1})$
$= 1.60 \times 10^{-10}\,\text{J}$,

it follows that

$$540\,\text{GeV} \approx 540\,\text{GeV} \times (1.60 \times 10^{-10}\,\text{J}\,\text{GeV}^{-1})$$
$$\approx 8.6 \times 10^{-8}\,\text{J}$$

(b) Zero. Because the particles collide head-on with the same kinetic energy, their momenta are of the *same* magnitude but of the *opposite* sign. Hence, the total momentum of the particles is zero.

SAQ 5 (c). Statement (c) is false because the μ^+ and the μ^- are both currently believed to be fundamental.

Statement (a) is correct because the μ^+ is the antiparticle of the μ^-. (Remember a particle has the same rest mass as the corresponding antiparticle.) Statement (b) is correct because the μ^+ and the proton both have charge $+e$. Statement (d) is correct because both the μ^- and the μ^+ have charge.

SAQ 6 (a) Yes, the first three lines apply equally well to antineutrinos, which also have zero (or nearly zero) rest mass and which interact only weakly and gravitationally with other matter (Table 3).

(b) The line is scientifically incorrect because neutrinos do interact, weakly and gravitationally, with other matter. A scientifically acceptable version of the line is 'and scarcely interact at all'.

(c) Photons pass through clear glass with only a small amount of scattering, which is why the glass is transparent. The Earth is, in this sense, almost transparent to neutrinos.

SAQ 7 Only reaction (c) can occur because only in this reaction are charge Q, baryon number B and strangeness S conserved:

$$\begin{array}{llll}
\text{(c)} & & K^- + p \rightarrow \bar{K}^0 + n & \\
& Q & -1 + 1 = \;\; 0 + 0 & Q \text{ conserved} \\
& B & \;\;\; 0 + 1 = \;\; 0 + 1 & B \text{ conserved} \\
& S & -1 + 0 = -1 + 0 & S \text{ conserved}
\end{array}$$

Reaction (a) cannot occur:

$$\begin{array}{llll}
\text{(a)} & & \pi^- + p \nrightarrow n + p & \\
& Q & -1 + 1 \neq 0 + 1 & Q \text{ not conserved} \\
& B & \;\;\; 0 + 1 \neq 1 + 1 & B \text{ not conserved} \\
& S & \;\;\; 0 + 0 = 0 + 0 & S \text{ conserved}
\end{array}$$

nor can reaction (b) occur:

$$\begin{array}{llll}
\text{(b)} & & \Sigma^- + p \nrightarrow K^0 + n & \\
& Q & -1 + 1 = \;0 \;+ 0 & Q \text{ conserved} \\
& B & \;\;\; 1 + 1 \neq \;0 \;+ 1 & B \text{ not conserved} \\
& S & -1 + 0 \neq \;1 \;+ 0 & S \text{ not conserved}
\end{array}$$

SAQ 8 The charge of particle X is approximately -1.602×10^{-19} C, X is a baryon and its strangeness is -3.

The question can be answered by writing down the values of the charge Q, baryon number B and strangeness S of the hadrons involved in the reaction, letting the values for each of these intrinsic conserved properties for X be Q_x, B_x and S_x:

$$\begin{array}{llll}
& K^- + p \rightarrow & K^0 + K^+ + X \\
Q & -1 + 1 & 0 \;+\; 1 \;+ Q_x \\
B & \;\;\; 0 + 1 & 0 \;+\; 0 \;+ B_x \\
S & -1 + 0 & 1 \;+\; 1 \;+ S_x
\end{array}$$

Because the interaction is known to be strong, it follows that charge, baryon number and strangeness must each be conserved. Hence, $Q_x = -1$, $B_x = 1$ and $S_x = -3$.

The statement $Q_x = -1$ means that the charge of X is minus one times the charge of the proton, i.e. $Q_x \approx -1.602 \times 10^{-19}$ C; because $B_x = 1$, X must be a baryon. This baryon was called Ω^-.

SAQ 9 Leptons (c) are currently believed to be fundamental. Mesons and baryons are types of hadrons, and it is known that hadrons have constituents, so they are *not* fundamental particles.

Because mesons and baryons, (a) and (b), are types of hadron they are by definition subject to strong interactions, whereas leptons are *not* subject to these interactions.

SAQ 10 Statements (a) and (c) are correct: quarks and antiquarks are currently believed to be fundamental (i.e. to have no constituents) and they exist in hadrons (Figure 25).

Statement (b) is false because leptons are currently believed to be fundamental particles (Section 3). Statement (d) is false because quarks and antiquarks are subject not only to strong interactions, they are also subject to gravitational interactions (in common with all other particles and antiparticles), to electromagnetic interactions (because they have charge) and to weak interactions. Statement (e) is false: no isolated quark or isolated antiquark has ever been observed.

SAQ 11 (a) $Q = 0, B = 1, S = -2$

$$\begin{array}{ll}
& \text{u} \;\; \text{s} \;\; \text{s} \\
Q & \tfrac{2}{3} - \tfrac{1}{3} - \tfrac{1}{3} = 0 \\
B & \tfrac{1}{3} + \tfrac{1}{3} + \tfrac{1}{3} = 1 \\
S & 0 - 1 - 1 = -2
\end{array}$$

(b) $Q = 1, B = 0, S = 0$

$$\begin{array}{ll}
& \text{u} \;\; \bar{\text{d}} \\
Q & \tfrac{2}{3} + \tfrac{1}{3} = 1 \\
B & \tfrac{1}{3} - \tfrac{1}{3} = 0 \\
S & 0 + 0 = 0
\end{array}$$

SAQ 12 (a): the J/ψ has constituents. It is a hadron (J/ψ = c$\bar{\text{c}}$). Each of the other particles listed is a quark or a lepton (or one of their antiparticles) and is currently believed to be fundamental, i.e. to have no constituents: (b) is a lepton, (c) is an antilepton, (d) is a quark and (e) is an antiquark.

SAQ 13 (a) $Q = 1, B = 0, S = 1, C = 1, T = 0, \mathsf{B} = 0$

$$\begin{array}{ll}
& \text{c} \;\; \bar{\text{s}} \\
Q & \tfrac{2}{3} + \tfrac{1}{3} = 1 \\
B & \tfrac{1}{3} - \tfrac{1}{3} = 0 \\
S & 0 + 1 = 1 \\
C & 1 + 0 = 1 \\
T & 0 + 0 = 0 \\
\mathsf{B} & 0 + 0 = 0
\end{array}$$

This hadron has been observed—it is called the D_s^+ and it has a rest mass of approximately 1.971 GeV/c^2.

(b) $Q = 0, B = 0, S = 0, C = 0, T = 1, \mathsf{B} = 0$

$$\begin{array}{ll}
& \text{t} \;\; \bar{\text{u}} \\
Q & \tfrac{2}{3} - \tfrac{2}{3} = 0 \\
B & \tfrac{1}{3} - \tfrac{1}{3} = 0 \\
S & 0 + 0 = 0 \\
C & 0 + 0 = 0 \\
T & 1 + 0 = 1 \\
\mathsf{B} & 0 + 0 = 0
\end{array}$$

At the time of going to print (1988), this meson has not been observed.

SAQ 14 Statement (c) is correct: the interactions of the quarks in the constituent protons and neutrons are mediated by gluons (Figure 42).

Statement (a) is false: the photon is currently believed to be fundamental, in common with all the other gauge bosons. Statement (b) is false: from the decay of the W^+, it cannot be concluded that the products are the particle's constituents. Rather, it can be concluded only that the energy of the W^+ can be converted into the kinetic energy and the energy equivalent to the rest masses of the stated products.

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